DISSERTATION

PREDICTING CUMULATIVE WATERSHED EFFECTS IN SMALL FORESTED WATERSHEDS

Submitted by

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In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Spring 2009

COLORADO STATE UNIVERSITY

January 26, 2009

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY SANDRA LITSCHERT ENTITLED PREDICTING CUMULATIVE WATERSHED EFFECTS IN SMALL FORESTED WATERSHEDS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

PREDICTING CUMULATIVE WATERSHED EFFECTS IN SMALL FORESTED WATERSHEDS

Cumulative watershed effects (CWE) are the physical and biological impacts that result from multiple land use disturbances over space and time. Land managers of forested watersheds are commonly required to assess the hydrologic and sedimentation impacts of timber harvest, road construction, and fires. Existing CWE models tend to range from checklists or indices that are subjective but inexpensive and simple, to complex physically based models that have large data needs and are difficult to apply. The primary goal of this research was to develop and test a series of models for assessing and predicting CWE that were designed to be easy to use, science-based, spatially explicit, and only require readily available data. Given the paucity of data on hillslope sediment delivery, a field study also was conducted to assess the frequency, characteristics, and connectivity of sediment pathways from timber harvest units.

The two CWE models developed in this research are: 1) Delta-Q, which calculates percent and absolute changes in the 1st, 50th, and 99th flow percentiles; and 2) FOREST (FORest Erosion Simulations Tools), which calculates sediment production and delivery from hillslopes and roads, and the downstream routing of sediment. The models were designed for use in watersheds of up to about 100 km^2. The models were verified using data from three watersheds on the Eldorado National Forest in California.

Delta-Q and FOREST were evaluated using data from Caspar Creek (CA), Mica Creek (ID), and H.J. Andrews (OR) Experimental Forests. The calculated changes in flows were more accurate for the 50th percentile than the 1st and 99th percentiles because

Delta-Q predicts mean values and the more extreme flows are more sensitive to fluctuations in annual precipitation. Predicted suspended and bedload sediment yields in FOREST usually fell within the range of measured values except at Caspar Creek during 1971-3 when a splash dam failed and released large amounts of sediment. Sensitivity analyses showed that FOREST is more sensitive to changes in DEM resolution and mean annual precipitation than to changes in maximum road and stream arc lengths.

The downslope edges of nearly 200 timber harvest units were traversed during the field study in the Sierra Nevada mountains of California. Only 19 rills or sediment plumes were found that originated from harvest units rather than roads. Five of the six features that extended through the streamside management zone to a stream channel were generated by runoff from skid trails. The results indicate that harvest units rarely deliver sediment to streams, but in some cases post-harvest skid trail treatments are needed to reduce concentrated surface runoff and sediment delivery to streams.

Delta-Q and FOREST are particularly useful in that they generate GIS layers to show the hillslopes, roads, and stream reaches with the greatest risk for erosion and sedimentation. Users can select and easily update the initial values and recovery rates for key parameters; the models provide online help files to facilitate this process. The modular structure allows the models to be easily updated or modified. The models represent a middle approach between commonly used, but simplistic empirical models and complex physically based models that are rarely used by land managers.

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ACKNOWLEDGEMENTS

A project of this scope is not possible without different types of help, support, and advice from many people and I would like to express my gratitude to all those who helped me. Firstly, I thank my advisor, Dr. Lee MacDonald for his stimulating comments, discussions, and support throughout all phases of the modeling and field work. Also I thank my committee members: Drs. Melinda Laituri, Brian Bledsoe, and Sara Rathburn for their help and encouragement.

Financial support was provided by the USDA Forest Service Region 5 and the Stream Technology Team, and I would like to particularly thank Brian Staab and John Potyondy. Thanks to Jack Lewis and Diane Sutherland from the Redwood Sciences Lab, USDA Forest Service Pacific Southwest Station for providing the data for Caspar Creek. Elizabeth Keppeler kindly took me on a tour of the North and South Fork watersheds and provided much of the background information. Thanks also to Tim Link, Enhao Du, Jason Hubbart, and Diana Karwan for sharing their data from Mica Creek. I very much appreciated the easy downloads of online data for the H.J. Andrews Experimental Forest. Numerous Forest Service personnel helped me with maps, information, directions, and bear stories.

Many thanks go to my family and my husband's family for their continuing love, support, and understanding. Also I thank my friends, fellow students, and especially the crafting gang for fun times, listening, and caring.

Lastly, this dissertation would not have made it without my two best friends: my husband, John for his patient love, ready humour, support, and the milestone margaritas, and finally Hitch for always reminding me to take time to hike, run, or play.

Table of Contents

Abstract....x
Table of Contents xi
List of Tables....xiii
List of Figures....xvi
Appendices....xix

Chapter 1. INTRODUCTION....1
1.1 Project background....1
1.2 Objectives and products....3
1.3 Organization....6
1.4 References....7

Chapter 2. DELTA-Q AND FOREST: MODEL DESCRIPTION AND VERIFICATION 9
2.1 Abstract....9
2.2 Introduction....10
2.2.1 Model complexity....12
2.2.2 Spatial representation....14
2.2.3 Objectives....15
2.3 Delta-Q....16
2.3.1 Background....16
2.3.2 Delta-Q algorithm, inputs and outputs....17
2.4 FOREST....19
2.4.2 Road sediment production....21
2.4.3 Hillslope sediment delivery....23
2.4.4 Road sediment delivery....29
2.4.5 Sediment routing....31
2.4.6 Suspended sediment transport....31
2.4.7 Bedload transport....32
2.4.7.1 Mean annual travel distance....34
2.4.7.2 Bagnold's method for bedload transport....34
2.5 Graphical user interface, GIS, and programming languages....39
2.6 Model verification and testing....40
2.6.1 Watershed descriptions....41
2.6.2 Delta-Q inputs....42
2.6.3 FOREST inputs....43
2.6.4 Results....46
2.7 Discussion....50
2.7.1 Potential uses of Delta-Q and FOREST....50
2.7.2 Limitations on modeling CWE....52
2.7.4 Research needs and model additions....55
2.8 Conclusions....56

2.9 References 58

Chapter 3. EVALUATION AND SENSITIVITY ANALYSES OF DELTA-Q AND FOREST..94
3.1 Abstract 94
3.2 Introduction 95
3.3 Evaluation sites and data availability..102
3.4 Methods..104
3.4.1 Inputs and simulations 104
3.4.2 Simulation analyses 106
3.4.3 Sensitivity analyses of FOREST 107
3.5 Results..109
3.5.1 Evaluation of Delta-Q..109
3.5.2 Suspended sediment 110
3.5.3 Bedload sediment 114
3.5.4 Sensitivity analysis of raster calculations 115
3.5.5 Sensitivity analysis of mean annual precipitation 117
3.5.6 Sensitivity analysis of maximum road arc length 117
3.5.7 Sensitivity analysis of maximum stream arc length..119
3.6 Discussion 120
3.6.1 Evaluation of Delta-Q..120
3.6.2 Evaluation of FOREST..122
3.6.3 Spatial scale, disaggregation, uncertainty, and error..126
3.7 Conclusions 129
3.8 References 131

Chapter 4 SEDIMENT DELIVERY PATHWAYS FROM HARVEST UNITS TO STREAMS 172
4.1 Abstract 172
4.2 Introduction 173
4.3 Study area..175
4.4 Methods..176
4.4.1 Data analysis 176
4.5 Results..179
4.6 Discussion 183
4.7 Conclusions 187
4.8 References 188

Chapter 5. CONCLUSIONS 201
5.1 CWE models: Delta-Q and FOREST 201
5.2 Sediment delivery pathways from harvest units to streams 203
5.3 Management recommendations..205
5.4 Future research 206
5.3 References 207

List of tables

Table 2.1. Combinations of factors used in the WEPP simulations to create look-up tables for sediment delivery. The factors used to determine the proportions of fine and coarse sediment are marked with an asterisk. 68

Table 2. 2. Range of predicted to observed bedload transport ratios for 12 formulae as calculated from 410 observations (adapted from Gomez and Church, 1989). 69

Table 2. 3. Total road length and total areas disturbed by timber harvest and fire by watershed. 70

Table 2.4. Area (km2) and type of timber harvests by year in Dogtown, Dry Creek, and Steely watersheds. 71

Table 2.5. Initial percent change in flow and number of years to recovery for different types of timber harvest and different fire severities. 72

Table 2.6. Initial sediment production rates (SP), years to recovery, and the initial land cover type assigned for undisturbed and disturbed hillslope. 73

Table 2.7. Parameter values for the equations used to calculate bankfull discharge (Qb) in cfs, bankfull depth (d) in ft, and bankfull width (w) in ft for each stream arc in the three watersheds, Da is the drainage area (mi2). Qb, d, and w are converted to cms and meters after calculation. 74

Table 2.8. Length of roads, mean arc length, road density, predicted road sediment production, and predicted road sediment delivered to streams by soil type and by watershed. 75

Table 2.9. Mean annual travel distance (MATD): a) model start-up time to attain background sediment yields and b) years for sediment to reach outlet after disturbance. .. 76

Table 3.1. Location, dominant vegetation, mean annual precipitation, and data used to evaluate and analyze Delta-Q and FOREST from Caspar Creek, H.J. Andrews, and Mica Creek experimental watersheds 137

Table 3.2. Initial changes in flow (DQ) and years to recovery for different types of forest harvest for the 1st, 50th, and 99th flow percentile simulations for Caspar Creek, H.J. Andrews, and Mica Creek. 138

Table 3.3. Input parameters to FOREST for the North Fork and South Fork of Caspar Creek from 1962 to 2004. 139

Table 3.4. Input parameters to FOREST for Watersheds 1 and 2 at Mica Creek from 1991 to 2005. 140

Table 3.5. Mean, standard deviation (s.d.), and coefficient of variation (C.V.) of the measured and predicted values for the 1st, 50th, and 99th percentile flows at the North Fork of Caspar Creek from 1990 to 2004, and the Nash-Sutcliffe efficiency and RMSE for the comparison of measured and predicted values using Delta-Q. 141

Table 3.6. Mean, standard deviation (s.d.), and coefficient of variation (C.V.) of the measured and predicted values for the 1st, 50th, and 99th percentile flow at Mack Creek, H.J. Andrews from 1980 to 1996, and the Nash-Sutcliffe efficiency and RMSE for the comparison of measured and predicted values using Delta-Q.......................................142

Table 3.7. Mean, standard deviation (s.d.), and coefficient of variation (C.V.) of the measured and predicted values for the 1st, 50th, and 99th percentile flow at Watersheds 1 and 2, Mica Creek from 2002 to 2005, and the Nash Sutcliffe efficiency and RMSE for the comparison of measured and predicted values using Delta-Q.......................................143

Table 3.8. Mean, standard deviation, and coefficient of variation of the measured and predicted annual suspended sediment yields at Caspar Creek from 1963 to 2004, and the Nash-Sutcliffe efficiency and RMSE for the comparison of measured and predicted values. 144

Table 3.9. Mean, standard deviation, and coefficient of variation of the measured and predicted annual suspended sediment yields at Mica Creek from 1992 to 2004, and the Nash Sutcliffe efficiency and RMSE for the comparison of measured and predicted values. 145

Table 3.10. Mean, standard deviation, and coefficient of variation, of the measured and predicted values for the bedload transport at the North Fork and South Fork of Caspar Creek from 1963 to 2004, and the Nash-Sutcliffe efficiency and RMSE for the comparison of measured and predicted values. 146

Table 3.11. The differences in annual road sediment production and delivery due to changing the DEM resolution from 10 to 30 m, mean annual precipitation from 900 to 1500 mm, and maximum road arc length from100 to 500 m, and using unaltered arc lengths for the North Fork and South Fork at Caspar Creek. 147

Table 3.12. The differences in the sensitivity index (S) for peak and total hillslope sediment delivered, and road sediment delivered when mean annual precipitation is changed from 900 mm to 1500 mm. The baseline simulation to calculate S used a mean annual precipitation of 1200 mm. 148

Table 4.1. Description of the five surface roughness classes….. .... …193

Table 4.2. Feature and site characteristics in order of increasing feature length. MAP is mean annual precipitation...194

Table 4.3. Correlation matrix for the predictor variables with r values on top and p-values below. Significant relationships ($p < 0.05$) are in bold. 195

List of figures

Figure 2.1. Spatial representation and algorithm complexity of selected models for assessing or predicting CWEs in forested watersheds. The two models in bold were developed as part of this research. 77

Figure 2.2. Schematic of different spatial representations in CWE models: a) lumped watershed; b) homogeneous polygons; c) OFEs linked by streams; and d) raster-based with hillslope flowpaths (not shown) and in-stream routing. 78

Figure 2.3. Inputs and outputs for Delta-Q. 79

Figure 2.4. Basic structure and flow of FOREST for predicting sediment production, sediment delivery, sediment routing and linkage to Delta-QR. 80

Figure 2.5. Flow chart of the sediment delivery procedure. (a) Data from WEPP hillslope profiles were used to create a lookup table (b). (c) Data from different GIS layers are coded digitwise into one layer. The coded layer is used to look up percent sediment delivered in the table and (d) create a GIS layer of percent sediment delivered for each cell. 81

Figure 2. 6. Boxplots of the predicted percent fine (< 0.062 mm) and coarse (0.062 - 2 mm) sediment delivered for a clay loam ("fine") soil and sandy loam ("coarse") soil. The black dots are median values; the boxes represent the 25th and 75th percentiles; the whiskers are ±1.5 times the inter-quartile range; and the grey diamonds are values outside of the whiskers. 82

Figure 2.7. Schematic of sediment delivery calculations along a simple hillslope flow path of n cells. The recursive algorithm in FOREST calculates percent sediment delivered for each cell beginning with the lowest cell along each flow path. 83

Figure 2.8. An example of the graphical user interface showing step-by-step input instructions, inputs from parameter files, input boxes for parameter values, and command buttons. 84

Figure 2.9. Location and topography of Dogtown, Dry Creek, and Steely watersheds in the Eldorado National Forest, California. 85

Figure 2.10.Areas disturbed by: a) different types of timber harvest, and b) fires of varying severities. Years indicate when an area burned. 86

Figure 2.11. Predicted changes in the 99th percentile flows by disturbance type for: a) Dogtown, b) Dry Creek, and c) Steely watersheds from 1970 to 2010. 87

Figure 2.12. Hillslope sediment production and delivery (Mg ha^{-1} yr^{-1}) to each stream arc in Dogtown, Dry Creek, and Steely watersheds for 1987, 1989, 1991, and 1993. 88

Figure 2. 13. Total hillslope sediment production (Mg km^{-2} yr^{-1}) for Dogtown, Dry Creek, and Steely watersheds from 1970 to 2010. 89

Figure 2.14. Amounts of fine and coarse hillslope sediment delivered to streams normalized by watershed area from 1970 to 2010 for: a) Dogtown; b) Dry Creek; and c) Steely. 90

Figure 2.15. a) Annual road sediment production (kg m^{-1} yr^{-1}) and b) road sediment delivered (kg m^{-1} yr^{-1}) to streams for Dogtown, Dry Creek and Steely watersheds. 91

Figure 2.16. Annual suspended sediment yields normalized by watershed area for Dogtown, Dry Creek, and Steely watersheds from 1970 to 2010. 92

Figure 2.17. Bedload sediment yields normalized by watershed area using: a) MATD and b) Bagnold's equation for Dogtown, Dry Creek, and Steely watersheds from 1970 to 2010. 93

Figure 3.1. Locations of the Caspar Creek, H.J. Andrews, and Mica Creek experimental watersheds used to evaluate Delta-Q and FOREST. The data from Caspar Creek also were used for the sensitivity analyses........ 149

Figure3.2. The locations of timber harvests, streams, and roads for the North Fork and the South Fork watersheds at Caspar Creek, California for 1971 to 1991. Years indicate when a timber harvest occurred........ 150

Figure 3.3. The locations of timber harvests, streams, and roads for Mack Creek and WS2 (control) at H.J. Andrews, Oregon. 151

Figure 3.4. The locations of timber harvest, streams, and roads for Watersheds 1, 2, and 3 (control) at Mica Creek, Idaho. Years indicate when a timber harvest occurred. 152

Figure 3.5. Comparison of predicted and measured changes in the 1st percentile flows for: a) Mack Creek at the H.J. Andrews, b) North Fork of Caspar Creek, c) Watershed 1 at Mica Creek, and d) Watershed 2 at Mica Creek. 153

Figure 3.6. Comparison of predicted and measured changes for 50th percentile flows for: a) Mack Creek at the H.J. Andrews, b) North Fork of Caspar Creek, c) Watershed 1 at Mica Creek, and d) Watershed 2 at Mica Creek. 154

Figure 3.7. Comparison of predicted and measured changes for 99th percentile flows for: a) Mack Creek at the H.J. Andrews, b) North Fork of Caspar Creek, c) Watershed 1 at Mica Creek, and d) Watershed 2 at Mica Creek. 155

Figure 3.8. Predicted and measured annual suspended sediment yields for: a) the North Fork, and b) the South Fork at Caspar Creek from 1965 to 2004. 156

Figure 3.9. Predicted and measured annual suspended sediment yields for: a) Watershed 1, b) Watershed 2, and c) Watershed 3 at Mica Creek from 1992 to 2004. 157

Figure 3.10. Predicted and measured annual bedload sediment yields using the mean annual travel distance (MATD) and Bagnold's equation for the a) North Fork and b) South Fork of Caspar Creek from 1963 to 2004. 158

Figure 3.11. Frequency distribution of 588 hillslope sediment delivery values from the WEPP look up tables using 20 m and 60 m hillslopes that correspond to the10 m and 30 m DEMs, respectively. Both sets of simulations used the Caspar Creek climate in the WEPP database. 159

Figure 3.12. Calculated hillslope sediment delivery for a) the North Fork and b) the South Fork at Caspar Creek from 1962 to 2010 using look-up tables derived with 20- and 60-m hillslopes corresponding to10 and 30 m DEMs, respectively. 160

Figure 3.13. Sediment yields calculated using a mean annual travel distance of 2400 m for a) the North Fork and b) the South Fork at Caspar Creek. At each site simulations used either the look up table for 20 m hillslopes with the 10 m DEM or the look up table for 60 m hillslopes with the 30 m DEM. 161

Figure3.14. Changes in the amount of hillslope sediment delivered from hillslopes as the mean annual precipitation is varied from 900 to 1500 mm for a) the North Fork and b) the South Fork at Caspar Creek from 1962 to 2005. 162

Figure3.15. Changes in the amount of bedload sediment yields using Bagnold's method as the maximum stream length is varied from the unaltered lengths to 300, 400, and 500 m for a) the North Fork and b) the South Fork of Caspar Creek from 1962 to 2005. Maximum unaltered stream lengths ranged up to almost 2500 m. 163

Figure 3.16. Comparison of road arcs length by gradients for unaltered road arcs, and roads with maximum arc lengths of 400 m and 100m. 164

Figure 4.1. Location of the four National Forests used to assess harvest unit connectivity. The black dots indicate the location of one or more of the rills and sediment plumes identified in this study. 196

Figure 4.2. Frequency of features by length class and the number connected to a stream channel. 197

Figure 4.3. Feature length versus mean annual precipitation. 198

Figure 4.4. Feature locations and mean annual precipitation. Some symbols represent more than one feature. 199

Figure 4.5. Average hillslope gradients decreased with increasing distance from the top of the rills (r^2=0.54; p=0.04). Bars are one standard deviation and the values below each bar represent the number of rills. 200

Appendices

Appendix A: Input and output data from 30 years of simulations and a silt loam soil using WEPP: Road for Mica Creek..168

Appendix B: Climate files...172

Chapter 1. Introduction

1.1 Project background

Land use, management activities, and natural disturbances alter the physical and biological characteristics of watersheds. The downstream impacts that result from multiple manmade and natural disturbances are referred to as cumulative watershed effects (CWE). Hydrologic CWE include changes in the magnitude and timing of peak flows, low flows, and annual water yields. Sedimentary CWE can result in increased sediment loads that alter channel morphology (Troendle and Olson, 1994, Madej and Ozaki, 1998), degrade aquatic and riparian habitat (Shaw and Richardson, 2001), reduce reservoir storage capacity, and adversely affect the supply and quality of drinking water (Dunne and Leopold, 1978; EPA, 2003). CWE can occur in any watershed, but this study focuses on CWE in forested watersheds.

Land managers must comply with a complex web of federal or local requirements when planning new activities. The prediction of CWE for activities on federal lands is required by The National Environmental Policy Act (NEPA). State and local laws, such as the California Environmental Quality Act, have similar requirements for other public lands, and the requirement for assessing CWE may extend to private lands. In addition to comparing future management scenarios within a watershed, CWE analyses may be conducted to compare current conditions across watersheds, future management scenarios across watersheds, and identify at-risk sites and sediment sources for mitigation and restoration.

Land managers have a wide range of tools to assess CWE. These tools generally fall into one of three classes: 1) simple indices or checklists; 2) conceptual and empirical models; and 3) complex process-based models. Indices and checklists are easy to use and require minimal data, but they lack objectivity, validation, and a scientific basis (Reid, 1993). At the other end of the spectrum, process-based models are often difficult to use, require numerous parameters, and require data that are difficult to measure or may not be available (Reid, 1993). In many cases these process-based models do not provide more accurate results than simpler empirical or conceptual models (Wilson *et al.,* 2001; Merritt *et al.,* 2003). Hence conceptual and empirical models can bridge the gap between these two extremes by providing quantitative solutions that are relatively easy to apply yet scientifically based.

Concern over CWE has led to extensive litigation in federal district and appellate courts. From 1995 to 2005 a number of federal CWE analyses have been successfully challenged due to technical problems or inadequate analyses (Smith, 2005; Reid, 2006). One problem was the failure to completely account for the CWE of past, present, and future activities (Reid, 2006). Secondly, the models used to analyze CWE were not sufficiently evaluated against measured data for the study area (Reid, 2006). A third problem is that the analyses did not adequately disclose model assumptions (Smith, 2005; Reid, 2006).

The scientific and legal failures of CWE analyses dictated three key needs that helped direct this research. First, the models need to facilitate temporally explicit analyses of past, present and future activities (Council on Environmental Quality, 1997). The problem is that the quantification of CWE over time is complicated by the temporal variability in climate, varying recovery times, and transmission delays within the stream network (MacDonald, 2000). Second, models need to be evaluated with measured data relevant to the sites and disturbances being considered in the CWE analysis. Third, model developers need to explicitly describe model assumptions and users need to clearly state the model assumptions in a given CWE analysis.

Spatial representation in existing CWE models ranges from spatially independent, such as watershed averages, to spatially explicit, raster-based models. The problem with lumped models using watershed averages is that they cannot account for the spatial variability in watershed processes or the interactions of watershed processes with spatially varying watershed characteristics such as topography, soils, and vegetation (Walling, 1983). In contrast, raster-based models can capture the cell-scale variability in watershed characteristics and processes. Another major advantage of raster-based models is that they can simulate drainage pathways for sediment routing and provide spatially explicit estimates at cell, hillslope, and stream reach scales. The problem is that spatially explicit models have not been used because of their complexity, data requirements, and run-time, but recent advances mean that these limitations are becoming much less of a concern.

1.2 Objectives and products

Given this background and context, the overall goal of this research was to develop and test conceptual and empirical CWE models designed to calculate changes in runoff, erosion, and sedimentation. The specific objectives were to:

1) Develop spatially explicit CWE models to predict changes in flow (Delta-Q) and sediment yield (FOREST- FORest Erosion Simulation Tools) from small forested

watersheds (<100 km^2) subject to disturbance from unpaved roads, forest management, and fires;

2) Verify each model using data from three watersheds on the Eldorado National Forest in California;

3) Validate each model using data from the experimental watersheds at Caspar Creek in northwestern California, H.J. Andrews Experimental Forest in western Oregon, and Mica Creek in northern Idaho;

4) Conduct sensitivity analyses of FOREST by varying the scale and resolution of GIS data inputs and mean annual precipitation; and

5) Assess the delivery of sediment to streams from areas disturbed by forest management activities in the Sierra Nevada of California.

The specific criteria for the development of these two CWE models were to: be spatially and temporally explicit; use existing GIS data; parameterize models with local data or data from the scientific literature; be simple and transparent in concept; be easy to use with a graphical user interface; be modular to aid updates; and facilitate assessments of uncertainty and sensitivity. The first model, Delta-Q calculates changes in runoff. The second model, FORest Erosion Simulation Tools (FOREST) calculates sediment production, delivery, and routing. Both models were designed to provide quantitative assessments of predictions of CWE for land managers. The algorithms in Delta-Q and FOREST are based on 13 sub-models or meta-analyses of published data. Each disturbance is tracked through time according to user-defined recovery periods.

Model verification tests that the internal logic of the models operated as intended and model evaluation tests model accuracy by comparison of model predictions to measured data. The verification utilized data from three watersheds in the Eldorado National Forest in California.

Delta-Q was evaluated using discharge data from Caspar Creek, Mack Creek in H.J. Andrews Experimental Forest, and Mica Creek. FOREST was evaluated using sediment yield data from Caspar Creek and Mica Creek. Each evaluation period included undisturbed periods, different types of forest harvest with varying recovery periods, and unpaved roads. Model assumptions are specified throughout the model development, verification, and evaluation phases described in this dissertation.

Any effort to analyze CWE inevitably raises questions about the scale and resolution (or cell size) of digital data and the resulting accuracy of model predictions. Of particular concern is the resolution of digital elevation model (DEM) data as larger resolution DEMs smooth topography (Cochrane and Flanagan, 2005). The length of road and stream segments also affect a variety of calculations that use length or area, and these include road sediment production and sediment routing (Bloschl and Sivapalan, 1995; Luce and Black, 1999). These concerns led to a sensitivity analysis using FOREST on how DEM size, road arc length, stream arc length, and mean annual precipitation affect predicted CWE.

In developing FOREST it became apparent that there was no simple model for hillslope sediment delivery that fit the model development objectives. Since there are very few data on hillslope sediment delivery in forested areas, a field study was conducted in the Sierra Nevada mountains of California to assess the frequency and connectivity of rills and sediment plumes from timber harvest areas to streams. This portion of the research focused on areas subjected to timber harvest as this is typically the largest area of disturbance in forested watersheds and harvested areas can generate one to five times more erosion than undisturbed areas (Motha et al., 2003). The results provide useful insights into the likely contribution of timber harvest units to CWE but the limited number of features identified in the field meant that the hillslope delivery model in FOREST required a more broadly applicable look-up table approach.

The models generate GIS layers to show likely sediment “hot spots” on hillslopes, along roads, and in streams at each stage of the calculations. Hillslope GIS layers show sediment sources and amounts of sediment produced. Stream layers show the amounts of sediment delivered to each arc for each year simulated. Annual changes in discharge and sediment yield are summarized for each watershed and each year simulated. The models can be used to predict the current CWE in different watersheds or predict CWE for different planning scenarios in a watershed or amongst watersheds. Land managers can use the models to minimize CWE by adjusting land management activities, timing, or locations. The spatially explicit nature of the models means that they can be used to identify hillslopes and stream reaches in greatest need of mitigation and restoration.

1.3 Organization

This dissertation is organized into five chapters. Chapter 1 is the overall introduction. Chapter 2 first explains the structure and algorithms of Delta-Q and FOREST. The second part of this chapter uses a case study in the Eldorado National Forest to verify the models and illustrate their capabilities. Chapter 3 presents the evaluation of Delta-Q and FOREST, and the results of the sensitivity analysis for FOREST. Chapter 4 presents the field study to assess the delivery of runoff and sediment from timber harvest units. Chapter 5 presents the overall conclusions from this study and identifies future research needs.

1.4 References

Council on Environmental Quality (CEQ), 1997. Considering cumulative effects under the National Environmental Policy Act. Washington, DC. 64 pp. plus app.

Dunne, T., and L. Leopold, 1978. *Water in environmental planning*. W.H. Freeman & Company, San Francisco, CA, 818 pp.

Bloschl, G., and M. Sivapalan, 1995. Scale issues in hydrological modelling: a review. *Hydrological Processes* 9: 251-290.

Cochrane, T.A., and D.C. Flanagan, 2005. Effect of DEM resolutions in the runoff and soil loss predictions of the WEPP watershed model. *Transactions of the ASAE* 48(1): 109-120.

Luce, C.H., and T.A.Black, 1999. Sediment production from forest roads in western Oregon. *Water Resources Research* 35(8): 2561-2570.

MacDonald, L.H., 2000. Evaluating and managing cumulative effects: process and constraints. *Environmental Management* 26(3):299-315.

MacDonald, L.H., and D.B. Coe, 2007. Influence of headwater streams on downstream reaches in forested areas. *Forest Sciences* 53(2): 148-168.

Merritt, W.S., R.A. Letcher, and A.J. Jakeman, 2003. A review of erosion and sediment transport models. *Environmental Modelling & Software* 18(8-9): 761-799.

Reid, L.M., 1993. Research and cumulative effects. USDA Forest Service General Technical Report PSW-GTR-141. Albany, California, 118 pp.

Reid, L.M., 2006. Understanding and evaluating cumulative watershed impacts. In: W.J. Elliot, and L.J. Audin (editors), *CWE for fuels management in the Western U.S.* http://forest.moscowfsl.wsu.edu/engr/cwe/. Accessed 2006.

Smith, M.D., 2005. Recent trends in cumulative impact case law, National Association of Environmental Professionals Annual Conference, Alexandria, VA, 14 pp.

Wilson, C.J., J.W. Carey, P.C. Beeson, M.O. Gard, and L.J. Lane, 2001. A GIS-based hillslope erosion and sediment delivery model and its application in the Cerro Grande burn area. *Hydrological Processes* 15(15): 2995-3010.

Chapter 2. Delta-Q and FOREST: Model Description and Verification

2.1 Abstract

Changes in discharge and sedimentation have long been recognized as critical concerns for forest management. Federal and state laws commonly require land managers to compare the cumulative watershed effects (CWE) of different forest management scenarios before management plans or policy changes can be implemented. Existing operational methods to assess or predict CWE tend to be simple checklists, indices, or lumped models. Physically based, spatially explicit models are available but are not widely used because they are too data intensive, costly, and complex. The goal of this research was to find a middle ground by developing a suite of models for assessing CWE that are easy-to-use, spatially and temporally explicit, and scientifically based.

Delta-Q and FOREST (FORest Erosion Simulation Tools) are coupled models designed to meet these criteria. Delta-Q calculates annual changes in selected flow percentiles from a watershed using a linear recovery equation. Required inputs are GIS layers of forest management activities and fires over time, and user-specified initial changes in flow and times to recovery for each type of disturbance. FOREST uses a variety of conceptual and empirical sub-models to calculate sediment production and delivery from hillslopes and roads, and routing through the stream network as suspended or bedload sediment. Required

inputs include sediment production and recovery coefficients, and GIS layers of fires, forest management, roads, streams, soils, and elevation. Each model has online help files that provide detailed instructions and summaries of published data to help users select model inputs. Results include tables of annual changes in flow, annual hillslope and road sediment production, annual hillslope and road sediment delivery, and annual sediment yield for each watershed. GIS outputs show the spatial distribution of sediment production, delivery, and routing over the time being simulated.

Delta-Q and FOREST were verified using data from three small watersheds in the Eldorado National Forest in California. The models performed as expected with clearcuts in one watershed causing small changes in flow and increased sediment yields. CWE in the other two watersheds were dominated by the effects of high and moderate severity fires. The results suggest that Delta-Q and FOREST will be useful because of their ability to: simulate the effect of different disturbances and recovery rates on hydrologic and sedimentary CWE over time; generate GIS layers that show the spatial distribution of sediment production and delivery over time; and identify stream reaches at the greatest risk for sedimentation.

2.2 Introduction

Cumulative watershed effects (CWE) are the overlapping effects of multiple land use activities on watershed processes during the “past, present and reasonably foreseeable future” (CEQ, 1997). The National Environmental Policy Act (NEPA, 1970) specifically requires that federal agencies submit an environmental impact statement for proposed activities (40 CFR 6.200). The regulations specify that decision makers must examine the cumulative effects of proposed management activities, and these frequently include CWE. This research focuses on hydrologic and sedimentary CWE. The hydrologic CWE being addressed here are the changes in low, median, and peak flows. The sedimentary CWE of concern are the changes in erosion and the resulting changes in suspended and bedload sediment yields at the hillslope, stream reach, and watershed scale.

Recent reviews show that forest harvest generally increases stream flows, but the changes in annual, peak, and low flows are a complex function of watershed processes and characteristics, climatic factors, and anthropogenic activities (e.g., Bosch and Hewlett, 1982; Austin, 1999; Jones, 2000). Harvesting from 15% to 50% of a forested watershed area usually leads to a measurable but transient increase in annual streamflow (Stednick, 1996). Increased stream flows persist if the reduction in canopy is maintained; otherwise the recovery of the vegetation will decrease water yields over time (MacDonald and Stednick 2003).

Increased runoff from forest disturbances also can cause increases in surface erosion and sediment delivery to streams. An increase in sediment loads can alter channel morphology (e.g., Troendle and Olson, 1994; Madej and Ozaki, 1998; Kreutweizer and Capell, 2001), degrade aquatic and riparian habitat (Shaw and Richardson, 2001), reduce reservoir storage capacity, and adversely affect the quality of drinking water (Dunne and Leopold, 1978; EPA, 2003). A number of pollutants, for example phosphorus and heavy metals, preferentially bind to fine sediment particles and the downstream transport of these pollutants is an important water quality concern (EPA, 2000). An increase in fine sediment also can have an adverse effect on the diversity and abundance of stream biota (e.g., Allan, 1995; Wood and Armitage, 1997).

Efforts to predict the cumulative effects of land use activities must account for changes in runoff and erosion over time and space (CEQ, 1997). Quantifying CWE over time is complicated by the temporal variability in climate, varying times to hydrologic and vegetative recovery, and transmission delays within the stream network (MacDonald, 2000).

A wide range of tools are available to assess CWE and these vary in their data needs, outputs, and skills required (Reid, 1993; Merritt *et al.*, 2003, Elliot *et al.*, 2006). Ideally, tool selection should be based on a dialog between land managers and modelers or experts to define the information needs, spatial extent of study areas, temporal context, organizational limitations in terms of employee skills and technology, required input data, format of output data, and user expectations with regard to the precision and accuracy of the results (Wilcock *et al.*, 2003; Caminiti, 2004; Elliot *et al.,* 2006). Users must understand the inherent limitations and assumptions of the chosen tool in order to use it effectively (Wilcock *et al.*, 2003; Caminiti, 2004).

2.2.1 Model complexity

The changes in flow, erosion, and sediment yield due to forest disturbances can be estimated by models and tools of varying algorithmic complexity and spatial resolution (Figure 2.1) (e.g., MacDonald, 2000; Borah, 2002; Merritt *et al.*, 2003; Elliot *et al.*, 2006). The simplest tools are subjective indices and checklists; these are inexpensive, easy-to-use, and heavily used by management agencies (Reid, 1993, MacDonald, 2000). Some commonly used indices include the Equivalent Roaded Area (ERA) and Equivalent Clearcut Area (ECA) (Cobourn, 1989; McGurk and Fong, 1995). The California Division of Forestry (CDF) has used qualitative checklists. The sediment delivery ratio (SDR) and its variations have been widely used to convert total erosion to watershed-scale sediment yields (e.g., Roehl, 1962; Walling, 1984; Fero and Porto, 2000). Indices and checklists may help identify problem areas that should be further investigated. However indices and checklists have important limitations as the coefficients are rough approximations, the results tend to be highly subjective, and the results are not spatially explicit (MacDonald, 2000).

Detailed process-based models fall at the upper end of the model complexity spectrum (Figure 2.1). Examples include the Distributed Hydrology, Soil, and Vegetation Model (DHSVM) (Wigmosta *et* al., 2002), MIKE-SHE, Soil Water Assessment Tools (BASINS-SWAT), and the Water Erosion Prediction Project (WEPP) (Merritt *et al.*, 2003). Process-based models can be difficult and expensive to parameterize, calibrate, and run, and they do not necessarily produce more accurate results (Reid, 1993; Wilson *et al.,* 2001; Merritt *et al.,* 2003).

Empirical and conceptual models provide a middle ground between simple indices and more complex process-based models (Figure 2.1). In theory there is a clear dividing line between empirical and conceptual models, as empirical models relate field observations to response variables (Merritt *et al.*, 2003) while conceptual models make predictions using *a priori* relationships (Dingman, 2002). In reality some models such as SEDNET or IHACRES-Q, include both empirical and conceptual equations so the distinction can be artificial (Merritt *et al.*, 2003). Empirical models are criticized because they do not capture the range of variability in watershed characteristics and because their application is limited to areas similar to where the data were collected (Merritt *et al.*, 2003). Conceptual models such as R1-R4, AGricultural Non-Point Source Pollution Model (AGNPS) and Hydrological Simulation Program—Fortran (HSPF) attempt to represent key processes with simplified equations that are generalize to multiple locations (Merritt *et al.*, 2003). Simple empirical or conceptual models may be more appropriate for modeling CWE because of the difficulties in using process-based models (Merritt *et al.*, 2003).

2.2.2 Spatial representation

As with model complexity, the spatial representation of models ranges along a spectrum from spatially independent, such as watershed averages, to spatially explicit, raster-based models (Figure 2.1). Tools such as the CDF checklist or the sediment delivery ratio (SDR) are spatially independent, watershed averages (Figure 2.2a). These tools do not account for variability in watershed processes or the interactions of watershed processes with watershed characteristics such as topography, soils, and vegetation (Walling, 1983).

The next level of complexity uses lumped area models to represent homogeneous units within a watershed. Single values are used to denote each characteristic within each unit, such as slope, soil, vegetation, or climate (Figure 2.2b). In the ERA (McGurk and Fong, 1995) and R1-R4 (USDA FS, 1981) models, the results from individual areas are summed to obtain a sediment yield for the watershed. Hillslope models are similar to lumped area models in that they divide the area being modeled into homogenous hillslopes, sometimes called overland flow elements (OFEs). OFEs are connected in an attempt to construct simplified hillslopes, i.e., runoff and sediment "flow" into lower OFEs or stream reaches from upslope OFEs. Hence a key difference between lumped and hillslope models is that hillslope models use stream reach elements to route discharge and sediment through the watershed (Figure 2.2c). OFEs and stream reaches are used in models such as the Water Erosion Prediction Project (WEPP) (Eliott *et al.*, 2006), Kineros2 (http://www.tucson.ars.ag.gov/kineros/) and the Hillslope Erosion Model (HEM-GIS)

(Wilson *et al.*, 2001). OFEs can be delineated manually or automatically by GIS (e.g., GeoWEPP: http://www.geog.buffalo.edu/~rensch/geowepp/).

The most spatially explicit models depend on raster layers of square cells to represent the area being modeled (Figure 2.2d). Parameter values are assigned to each raster cell hence spatially explicit models can have a much finer resolution than hillslope models. Raster-based models use a DEM to account for complex topography, create drainage pathways, and to route sediment to stream channels. Such models explicitly simulate the spatial linkages between disturbances to the resources of concern. A spatially explicit approach has been used with very simple empirical models (Sun and McNulty, 1998) as well as more complex process-based models such as DHSVM (Wigmosta *et al.*, 1994) and ANSWERS (Beasley and Huggins, 1982).

For management and assessment purposes there is often a need for spatially explicit models that provide a middle ground between inexpensive, simple indices and costly, complex models. Hence the goal of this research was to develop models for assessing and predicting CWEs that are spatially explicit but still rely on conceptual or empirical algorithms in order to be more usable. To be both defensible and readily usable, such models must be scientifically based; use existing GIS data; parameterize models with local data or data from the scientific literature; be easy to use with a graphical user interface (GUI); be modular to aid updates; and facilitate uncertainty and sensitivity assessments.

2.2.3 Objectives

The first objective of this research was to develop spatially explicit CWE models to predict changes in flow (Delta-Q) and sediment yield (FORest Erosion Simulation Tools or FOREST) in small forested watersheds (<100 km^2) subject to disturbance from unpaved roads, forest management, and fires. The second objective was to verify that Delta-Q and FOREST are mathematically correct and function as designed. The second objective was achieved by testing the models using data from three watersheds in the Eldorado National Forest, California. This verification also provided an opportunity to test and display the functionality of each model for assessing CWE.

2.3 Delta-Q

2.3.1 Background

A key concern in many CWE analyses is the prediction of changes in low, median, and peak stream flows as a result of forest harvest, roads, and fires. Numerous studies have shown that a reduction in canopy cover due to forest harvest decreases interception and transpiration (e.g., Jones, 2000; MacDonald and Stednick, 2003). Ground-based harvesting can cause compaction which reduces infiltration and can initiate surface runoff. These changes in the water balance and runoff pathways will generally increase both peak and annual stream flows (Jones, 2000).

As vegetation grows back following forest harvest, evapotranspiration and interception increase and this means that the harvest-induced increases in runoff will decline over time (Troendle and King, 1985). The rate of hydrologic recovery varies with climate (Baker, 1986; Troendle and Nankervis, 2000; Jones and Post, 2004), vegetation type (Troendle and Nankervis, 2000), and aspect (Baker, 1986). A linear decline in annual water yields after forest harvest has been documented for paired watershed studies in Colorado (Troendle and Nankervis, 2000) and Oregon (Jones, 2000) and the linear recovery concept was used to develop Delta-Q.

2.3.2 Delta-Q algorithm, inputs and outputs

Delta-Q is designed to calculate watershed-scale, annual changes in peak, median, and low flows over time from areas disturbed by forest management and fires. The implicitly assumes that the hydrologic effects of roads are included in the effects of timber harvests since the watershed-scale data on the hydrologic effects of forest management almost always includes the effects of access roads.

The GUI leads users through the input of GIS layers with polygons of forest harvest or fires that include information on the year that each disturbance occurred (Figure 2.3). The user first selects whether to calculate absolute or relative changes in flow, as this determines the units of subsequent inputs. For each disturbance type, the user must define an initial change in flow and the number of years for hydrologic recovery. The user also must specify whether changes are to be calculated for the 1^{st}, 50^{th}, or 99^{th} percentile flows. If there is more than one disturbance layer, the user has the option to combine the effects of both disturbance types using a function which selects the maximum changes in flow for each area (Figure 2.3). In keeping with the user-friendly objective, online help files list management-induced changes in the 1^{st}, 50^{th}, and 99^{th} flow percentiles for 26 paired watershed experiments in widely varying locations (Austin, 1999).

The predicted changes in runoff are summed over the catchment being modeled using equations for percent (Equation 2.1) or absolute (Equation 2.2) changes:

$$D(Q) = \sum_{i=1}^{m} d(q_i)\left[1 - \frac{x_i}{n}\right]\frac{A_i}{AWS} \tag{2.1}$$

$$D(Q) = \sum_{i=1}^{m} d(q_i)\left[1 - \frac{x_i}{n}\right]A_i \tag{2.2}$$

where: $D(Q)$ is total change in flow in the watershed being modeled; $d(q_i)$ is the initial change in runoff in absolute (cfs/mi^2) or percentage terms for each disturbed area; i is the area identification number; m is the total number of disturbed areas; x_i is the years since disturbance in area i; n is the number of years to full hydrologic recovery; A_i is the area of disturbance (mi^2); and AWS is the area of the watershed. Equations 2.1 and 2.2 show that changes in flow are propagated unchanged through the watershed.

The primary output of Delta-Q is the predicted changes in runoff for each watershed. The outputs are summarized in tables listing the user-defined absolute or relative changes in flow for each watershed and each year being modeled (Figure 2.3).

Delta-Q is coupled with FOREST through Delta-QR, which calculates the relative changes in 99th percentile flows (Equation 2.1) in raster format. Inputs for Delta-QR are the same inputs as for Delta-Q (Figure 2.3). A separate raster is generated for each year that disturbances affect the watershed. The flow change rasters are used in the Bagnold sediment routing algorithm described in the FOREST bedload transport sub-model (Section 2.3.7).

Delta-Q is best used for modeling watersheds less than 100 km^2 as it implicitly routes the calculated changes in flow to the watershed outlet in the same year that the flow is generated. Delta-Q should be applicable for a wide range of geographic regions since users can assign values that are appropriate for their area of interest. Delta-Q could also be applied to other land uses where vegetation is altered, such as urbanization or down-hill ski areas but help files were not developed for other changes in land use.

2.4 FOREST

FOREST is a suite of models for calculating spatially explicit changes in erosion and sediment yield from forest management, fires and roads. FOREST comprises three main components that successively calculate: 1) hillslope and road sediment production, 2) sediment delivery from hillslopes and roads to streams, and 3) sediment routing for suspended and bedload sediment (Figure 2.4). These three components of FOREST are closely coupled as the sediment production values become inputs to the sediment delivery component, and the outputs from the sediment delivery component are inputs to the sediment routing component. The predicted changes in peak flows from Delta-QR can be automatically imported to FOREST since the calculated changes in the 99^{th} percentile flows can affect bedload routing.

2.4.1 Hillslope sediment production

Hillslope sediment production is primarily a function of precipitation, vegetation cover, slope length, slope gradient, and soil type (Reid, 1993; Lane *et al.*, 1997). Natural or anthropogenic disturbances can increase surface erosion by orders of magnitude over undisturbed hillslopes (e.g., Megahan, 1972; Coe, 2006). Similarly, high severity wildfires can increase sediment production by orders of magnitude as compared to undisturbed forests (Moody and Martin, 2001; Neary et al., 2005).

The hillslope sediment production sub-model is similar to the equations used in Delta-Q as the sub-model also assumes a linear decline in sediment production over time for disturbed areas (Equation 2.3):

$$SP = \sum_{i=1}^{m} \begin{cases} sp_i * \left[1 - \frac{x_i}{n_i}\right] * w_i \\ b_i \end{cases} \tag{2.3}$$

where SP is the total sediment production in the watershed being modeled (Mg); sp_i is the initial sediment production for each disturbed area (Mg ha^{-1}); i is the individual cell; m is the total number of cells; x is the years since activity; n is the number of years to reach background SP rates; w is the weighting factor; and b is the background sediment production rate used for undisturbed areas. In this equation, undisturbed or fully recovered areas are assigned a background sediment production rate (b); the windows-based interface allows users to easily modify the default value of 0.1 t ha^{-1} yr^{-1} (Riebe *et al*., 2000).

User inputs include GIS polygon layers with the type and year of disturbances. For each type of disturbance the user must provide an initial sediment production rate (sp) and the number of years required to return to the background rate. The weighting factor (w) allows the user to adjust the sediment production values according to another spatially variable controlling factor, such as geology or soil type. This factor needs to be in a separate GIS layer, and the default value for w is 1. Help files list published sediment production rates for forest harvest and burned areas, including the citation for each value.

Input values and layers are automatically saved to a parameter file which allows FOREST to restart from a point at which it was shutdown.

GIS layers of sediment production in Mg ha^{-1} yr^{-1} are calculated for each disturbance type for each year being modeled. If disturbances overlap, the sub-model selects the maximum cell value from the different layers. The sub-model also generates tables of annual sediment production for each watershed and each year being modeled.

2.4.2 Road sediment production

Unpaved roads are often the dominant source of sediment in forested watersheds (Megahan, 1972; Sun and McNulty, 1998, Croke *et al.*, 1999). The main factors controlling road sediment production are road segment length or area, road gradient, rainfall erosivity, time since construction or grading, traffic, and soil type (Campbell, 1984; Ketcheson and Megahan, 1996; Luce and Black, 2000; Ziegler *et al.*, 2000; MacDonald *et al.*, 2001; Coe, 2006). Road segment length can be substituted for contributing area if the roads are a consistent width. Road gradient is a surrogate for the energy available for erosion (Luce and Black, 2000). Time since construction or grading is important as this affects the amount of surface material is available for detachment and transport on newly constructed roads (Coe, 2006). Traffic decreases the infiltration rate and increases the amount of loose material on the road surface (Ketcheson and Megahan, 1996; Ziegler *et al.*, 2000; Coe, 2006).

FOREST has two empirical sub-models for calculating road sediment production or users can also specify road erosion rates based on local knowledge or other model simulations. Users will need to input a vector GIS layer of roads. The first empirical sub-model was developed in the central Sierra Nevada of California (Coe, 2006):

$$SP\ (\text{kg/yr}) = -356+106*G+3.3*A*S+0.6*TE \qquad (2.4)$$

where G has a value of 1 if a road was graded within the last two years, and 0 if the road has not been recently graded. A is the road arc area (m^2), and this is calculated in FOREST using the product of the user-defined width and the length of the road arc ascertained from the roads layer. The arc slope, S ($m\ m^{-1}$) is calculated from the DEM for each arc as the difference in elevation between the beginning and end of the road arc divided by the arc length. Total erosivity, TE ($MJ\ mm\ ha^{-1}\ hr^{-1}\ yr^{-1}$), is the annual sum of the storm energy multiplied by the maximum 30-minute rainfall intensity for each storm (Renard *et al.*, 1997). Isoerodent maps of total erosivity are provided in FOREST for the eastern and western U.S., California, Oregon and Washington (Renard *et al.*, 1997).

The second empirical sub-model for calculating road erosiom was developed in western Oregon (Equation 2.5):

$$SP \text{ (kg yr}^{-1}) = a * L * (S)^2 \qquad (2.5)$$

where a is an empirical coefficient with a default value of 717 (Luce and Black, 1999). L(m) is the length of each road arc and S (m m^{-1}) is the slope of the road arc calculated using the DEM. The interface allows the user to adjust a to more accurately predict local road erosion rates.

Users also can specify a sediment production rate for all roads or different types of roads as indicated by a descriptor in the GIS. These sediment production rates can be obtained from other models, such as WEPP:Road (http://forest.moscowfsl.wsu.edu/fswepp/) or SEDMODL2 (www.ncasi.org/). None of the models listed or described here includes a provision for a decline in road sediment production rates. To account for changes in roads, users can run multiple simulations with different road inputs.

Road arc length affects road sediment production (equations 2.4, 2.5) and the accuracy of the road slopes as calculated from the DEM. Road arc length is usually determined by a change in road characteristics or a road junction, and there can be considerable variability in road arc lengths in the GIS roads layer. Since shorter arc lengths will result in more accurate road gradients and improve the accuracy and resolution of the road sediment production and delivery data, a GIS program was written to subdivide arcs longer than a user-specified maximum length. The program automatically copies the feature characteristics from the original arc to the newly created arcs by keeping track of arc identification numbers. The GUI gives users the option to specify the maximum road arc length and run this program before it calculates road gradients.

The outputs for road sediment production are stored in a field in the roads GIS layer. FOREST also generates a table that list road sediment production for each watershed; if only one watershed is being modeled, annual road sediment production is shown in a dialog box.

2.4.3 Hillslope sediment delivery

The hillslope sediment delivery sub-model determines what proportion of sediment being produced on the hillslope is delivered to the stream network for each raster cell. In forested areas, the transport and delivery of sediment from hillslopes to streams is very complex, and studies have shown that hillslope sediment delivery depends on: hillslope gradient and length; the amount and texture of the sediment available for transport; percent vegetation cover; surface roughness due to ground vegetation, litter, woody debris, and micro-topography; the amount and pathways of overland flow; and climate (Lane, 1982; Rogers, 1989; Lane *et al.*, 1997; Rice *et al.*, 2000; Lacey, 2000; Johansen *et al.*, 2001; Rivenbark and Jackson, 2004; Litschert and MacDonald, 2004).

The complexity of hillslope sediment delivery and relative paucity of field data for forested areas means that there are no widely used, spatially explicit models for predicting sediment delivery that could be incorporated into FOREST. Hence a look-up table approach was derived using the current state-of-the-art, physically based Water Erosion Prediction Project (WEPP) (http://topsoil.nserl.purdue.edu/nserlweb/weppmain/) model.

The WEPP model consists of coupled modules for stochastic weather generation, snow hydrology, infiltration, plant growth, plant senescence and decay, flow hydraulics, erosion, and sediment transport. WEPP uses lumped hillslope profiles that can be subdivided to represent changes in slope, soils, or vegetation. Different hillslopes can be simulated and combined to recreate simplified watershed topography. The overland flows from each hillslope are combined with soil, vegetation, and slope characteristics to calculate the sediment transport capacity. This transport capacity, using the kinematic wave equation, is used to predict the amount of sediment that is delivered to the base of each hillslope. The WEPP model has been adapted for modeling forested hillslopes by incorporating programs for predicting climate in mountainous areas and databases of empirical parameters for forest vegetation, management activities, and fire (Robichaud *et al*., 1993; Elliot, 2004). The recommended use of WEPP is limited to watersheds up to about 2.6 km^2.

Given this background, a series of simulations were conducted using the WEPP model to develop a series of look-up tables for predicting hillslope sediment delivery. More specifically, the look-up tables provide values for the percent of sediment delivered from a given GIS raster cell to the next cell downslope for different combinations of controlling factors. To use these look-up tables, FOREST determines a flow path to the stream network for every cell in the watershed and calculates sediment delivery on a cell-by-cell basis along each flow path.

Each WEPP simulation used a 20 m long hillslope profile as this hillslope length corresponds to two raster cells in a 10 m DEM. Individual hillslope profiles were created for each possible combination of six slopes, seven upslope and seven downslope land cover types, and two soil types, for a total of 588 simulations for a given climate (Table 2.1; Figure 2.5a). To reduce the number of possible combinations, percent slope was classified as follows: slopes of 0 to 5% were assigned to 1%; slopes >5 and ≤15% were assigned to 10%;

slopes >15 and ≤25% were assigned to 20%; and so on (Table 2.1). Slopes >45% were assigned to 50%, as sediment delivery in WEPP is not sensitive to slope once the slope exceeds 50%. Flat slopes between 0 to 5% will deliver very little sediment; hence these are represented by 1%.

The seven land cover types were obtained from the Disturbed WEPP database (http://forest.moscowfsl.wsu.edu/fswepp/) that is incorporated into WEPP. The sequence of land cover types listed in Table 2.1 was selected to represent the sequence of vegetation recovery after a high severity fire and timber harvest. For example the sequence that begins with a 5-year old forest could be used to represent recovery after a select cut. Look-up tables were generated for eight of the 2600 climate stations in the Cligen:WEPP database. These stations were chosen to represent a range of climates in California, Idaho, and Colorado (Table 2.1) that reflect the likely interests and locations of model users and the funding provided by the USDA Forest Service Region 5 and the Stream Technology Team. In a few cases, the sediment delivery values exceeded 100% so the maximum value in the look-up tables was set to 100%.

The WEPP model calculates sediment production and delivery for each of five particle size classes: sand; silt; clay; large aggregates consisting of sand, silt, and clay; and small aggregates consisting of silt and clay. In FOREST these five textural classes were grouped into two classes - fine sediment (<0.062 mm) and coarse sediment (≥ 0.062 mm to ≤ 2 mm) sediment because these largely correspond to suspended and bedload sediment respectively (Gomez, 1991). Particle sizes larger than 2 mm are not included because these larger particles generally represent a small fraction of the surface erosion from forest management, roads, and fires (e.g., Beaty, 1994; Luce and Black, 1999). These smaller particles also are of greatest concern as they preferentially combine with contaminants to be transported downstream (EPA, 2003), and they have a greater adverse effect on the feeding and reproduction of salmonids and benthic macroinvertebrates (Allan, 1995).

The relative proportions of fine (SD_f) and coarse sediment (SD_c) being delivered from each cell was assigned according to the results of 144 WEPP simulations using 20 m hillslope profiles (Figure 2.6). These WEPP simulations used two soils (clay loam and sandy loam), four different climates, the same six slope gradients, and three land-cover types (Table 2.1). The results of the 72 simulations for each soil showed very few differences in the percent of fine and coarse sediment being delivered except in the very dry climate when no sediment was delivered (Figure 2.6). These results mean that the median values are usually a reasonable representation of the percent of fine and coarse material being delivered (Figure 2.6). Hence, FOREST uses the median values to partition the mass of sediment delivered from areas of fine-textured soils into 75% fine and 25% coarse particles, while the delivery of sediment from areas of coarse-textured soils is assumed to be 53% fine and 47 % coarse particles.

The FOREST documentation includes a detailed description of the procedures used in WEPP and Microsoft Excel to create the look-up tables for each climate. Detailed step-by-step instruction files are included to help users create a sediment delivery look-up table for their location using WEPP and MS Excel. WEPP hillslope profile and project batch files are bundled with FOREST online as a .zip file.

To run the sediment delivery component in FOREST, users must provide a DEM, a soil texture raster layer, and select a climate with an associated look-up table for percent sediment delivered (Figure 2.5c). FOREST uses the DEM to calculate a percent slope layer and flow direction layer using the D8 algorithm (O'Callaghan and Mark, 1984). Percent slope is classified as explained above. Users must select one of the seven land cover types from Table 2.1 to represent each unique land cover type in the GIS layer. The soil texture raster must be coded 1 for clay and silt loams and 2 for coarse textured soils such as a sandy loam.

The land cover and flow direction layers are used to develop a new GIS layer specifying the land cover type for the cell immediately downslope of each cell. This downslope land cover layer, when combined with the original land cover layer, provides the upper and lower land cover types that correspond to one of the WEPP hillslope profiles (Figure 2.5). A digit-wise coding scheme is used to create an integer layer where the value for each cell identifies the slope class, the land cover types for the cell and the downslope cell, and the soil texture class for that cell. Using the code for each cell, FOREST retrieves the percent sediment delivered for each cell from the look-up table (Figure 2.5d).

A recursive algorithm is then used to calculate the total sediment delivered for each hillslope flow pathway. This algorithm traverses upslope through the stream network and each hillslope flow pathway, and it successively multiplies the percent sediment delivered for each cell along each flow pathway (Figure 2.7). The total percent sediment delivered for each cell is the cumulative product of the percent sediment delivered for all downslope cells multiplied by the percent sediment delivered (SD) for the current cell (Figure 2.7; Equations 2.6 to 2.8). The subscripts 1 to n represent the different cells along the flow path (Figure 2.7; Equations 2.6 to 2.8). The total percent sediment delivered to each cell is saved to a new raster.

The total amount of fine sediment delivered for each cell is calculated by multiplying the total percent sediment delivered ($\%SD_n$) by the sediment produced by that cell (SP_n) and the percent of fine particles (SD_f) for the soil type of that cell (Equation 2.9).

$$\text{Total fine } SD_n = \text{total } \% \ SD_n * SP_n * SD_f \tag{2.9}$$

Similarly, the total coarse sediment delivered for each cell is the product of the total percent sediment delivered, the sediment produced by that cell, and the percent of coarse particles (SD_c) for the soil type of that cell (Equation 2.10).

$$\text{Total coarse } SD_n = \text{total } \% \ SD_n * SP_n * SD_c \tag{2.10}$$

The percentages of fine and coarse sediment delivered from each hillslope flow path are summed to determine the annual amounts of fine and coarse sediment delivered to each stream arc for each year being simulated.

The amount of sediment being delivered from forest harvest, fires and other disturbances declines over time as regrowth occurs. FOREST automatically generates new GIS land cover layers for each year to follow the recovery sequence specified in Disturbed WEPP and Table 2.1. Each land cover type is assumed to change to the next land cover type after one year, except that the effects of a high severity fire are assumed to last for two years (Benavides-Solorio and MacDonald, 2005; Larsen and MacDonald, 2007), and a 5-year old forest must grow for 10 years before changing into a 20-year old forest (http://forest.moscowfsl.wsu.edu/fswepp/). In the FOREST GUI, users choose where they want to start the recovery sequence for each disturbance type by specifying one of the seven land cover types.

FOREST outputs include: 1) a GIS stream layer with the annual amounts of coarse and fine sediment delivered to each stream arc for each year being modeled; and 2) an MS Excel spreadsheet listing the amounts of fine and coarse sediment delivered to the streams in each watershed for each year being modeled. The GIS layers generated by FOREST allow the user to determine and map the amounts of sediment being generated and delivered at the hillslope, stream arc, and watershed scales, and these have obvious utility for guiding management decisions and identifying restoration priorities.

2.4.4 Road sediment delivery

The proportion of roads that are connected to streams within a watershed is strongly related to the mean annual precipitation because both road and stream density increases with increasing precipitation (Coe, 2006). Within a watershed the primary factor controlling road-stream connectivity is the proximity of road segments to streams; midslope and ridgetop roads are generally less likely to deliver sediment to streams (Ziegler *et al.*, 2000; Croke and Mockler, 2001). Much of the road-related sediment is delivered to streams at stream crossings (Croke and Mockler, 2001; Coe, 2006) and in the central Sierra Nevada stream crossings account for 59% of the road-stream connectivity (Coe, 2006). Given the difficulty in determining which road segments are connected, FOREST uses these general trends to assume that all of the sediment from road segments within a certain distance of a stream will be delivered. This distance is defined as the sediment delivery zone.

FOREST has two methods for determining the width of the sediment delivery zone. In the first method, the user specifies the width based on local knowledge. The second method uses an empirical equation to predict the percent of roads connected to streams (*PRC*). A meta-analysis of 11 published studies shows that 75% of the variability in the percent of roads connected is explained by the mean annual precipitation (*MAP*) (Equation 2.11) (Coe, 2006).

$$PRC = 7.98 + 0.0182 * MAP \text{ (mm)} \tag{2.11}$$

The GUI prompts the user to enter the MAP, and FOREST calculates the length of connected roads by multiplying the total length of roads in the area of interest by the percent of connected roads using Equation 2.11. FOREST surrounds the stream arcs with a buffer that is iteratively widened in 10 m increments until it includes the calculated length of connected roads.

The relative proportion of fine and coarse sediment being delivered from roads is calculated by superimposing the soils raster on the connected roads layer. The soils raster must be coded as either clay and silt loams (1) or sandy loams (2); the same raster is used for the roads and hillslope sediment delivery sub-models. The proportions of fine and coarse sediment are determined by the same SD_f and SD_c coefficients used in the hillslope delivery sub-model.

The required inputs for calculating road sediment delivery include a GIS road layer with sediment production values calculated by FOREST or provided by the user, a stream layer, a coded soil raster, and either a user-specified sediment delivery zone or the mean annual precipitation. FOREST outputs include: 1) the GIS stream layer with the annual amounts of fine and coarse road-related sediment delivered to each stream arc; and 2) a Microsoft Excel spreadsheet listing the total amounts of fine and coarse road-related sediment being delivered to all the streams in each watershed.

2.4.5 Sediment routing

Sediment transport through the stream network is a complex function of: flow magnitude and duration; sediment supply; the size, shape and density of sediment particles; stream channel characteristics, such as hydraulic geometry, gradient, and the amount of large woody debris; and fluid density and viscosity (Beschta, 1978; Lewis and Ziemer, 1998; Knighton, 1998; Bunte and MacDonald, 1999; Lancaster *et al.*, 2002).

Fine sediment is often transported long distances as suspended sediment, while coarser particles are typically transported much shorter distances as bedload (Knighton, 1998). Particle size alone cannot uniquely distinguish between bedload and suspended load because the particle sizes transported as bedload at low discharge may be transported as suspended sediment at higher flows (Knighton, 1998). Sand is the size range that most frequently shifts between bedload and suspended sediment (Knighton, 1998).

Most CWE studies are conducted in ungaged watersheds that do not have spatially and temporally explicit discharge and sediment transport data. Given this lack of data, FOREST assumes that particles smaller than 0.062 mm will be transported as suspended load and particles larger than fine sand (i.e., $\geq$ 0.062 mm) will be transported as bedload (Knighton, 1998). Hence FOREST has a sub-model for routing suspended sediment and two sub-models for routing bedload sediment.

2.4.6 Suspended sediment transport

Generally, suspended sediment in small streams is transported quickly through stream networks except at the lowest flows (Duncan *et al.,* 1987). In larger rivers the annual suspended sediment loads measured at least 30 km apart are in-phase (Waythomas and

Williams, 1988). These results suggest that suspended sediment is generally supply limited and flushed through the stream network annually (Waythomas and Williams, 1988; Knighton, 1998). Given the size of the watersheds for which FOREST was designed, FOREST assumes that particles finer than 0.062 mm are routed to the outlet of each watershed on an annual basis. Hence FOREST calculates the annual suspended sediment yield (*SS*) by:

$$SS = \sum_{i=1}^{n} SD_{f(i)} \tag{2.12}$$

where i is a stream arc and SD_f is the annual amount of fine sediment being delivered from the hillslopes and roads to each stream arc.

The required GIS input is the stream layer with the fine textured sediment delivery values for hillslopes and roads as calculated by FOREST, and these inputs are automatically read from the parameter file. The output from FOREST is a spreadsheet of the annual suspended sediment yields for each watershed and each year being simulated.

2.4.7 Bedload transport

Many models have been formulated to predict bedload transport. Process-based bedload formulae typically require channel geometry, particle size, and discharge data that are rarely available throughout a watershed (Gomez and Church, 1989; Knighton, 1998). The complexity of bedload transport means that process-based models typically require some simplifying assumptions, such as an idealized channel shape, and either a uniform sediment size or a single sediment size to characterize the sediment being transported. Bedload transport rates per unit stream width can be predicted from excess shear stress (Duboys-type equations), excess discharge per unit stream width (Schoklitsch-type equations), and excess stream power per unit width (Bagnold-type equations) (Knighton, 1998). Each of these three types of equations requires one or more hydrologic variables (i.e., flow velocity, flow depth, energy gradient or water surface slope, or discharge).

At least two studies have compared the accuracy of all three types of bedload transport equations and these results have helped guide the bedload transport procedures developed for FOREST. Gomez and Church (1989) tested 12 process-based and conceptual bedload transport equations against a dataset of 410 observations from seven natural rivers and flume experiments. Model performance was rated by the ratio of predicted to observed bedload transport rates, and Bagnold's (1980) equation was the most accurate (Table 2.2). A second, more recent study tested seven bedload transport equations against data from 22 streams; this also found that Bagnold's stream power equation was one of the most accurate (Bravo-Espinosa *et al*., 2003).

Users of FOREST are unlikely to have the field data, experience, or the computer capability to model flow and sediment routing processes in a spatially explicit manner at the watershed scale. Given the modeling objectives, the temporal and spatial scales of the areas being modeled, the capability of the users, and data availability, two bedload transport sub-models were developed for use in FOREST. The first uses an empirical sub-model of mean annual travel distance. The second sub-model has two conceptual solutions to Bagnold's equation. Particle sizes larger than 2 mm are not included as explained in Section 2.4.3. The bedload transport sub-models also do not account for bed or bank erosion as these sediment sources are very difficult to predict, and the primary modeling goal was to assess the cumulative effects of increased discharge and surface erosion from forest management, roads and fires.

2.4.7.1 Mean annual travel distance

The first sub-model for routing bedload sediment uses an estimate of the mean annual travel distance (MATD). A meta-analysis of 16 published values indicated that the mean annual travel distance was 2400 m when the D_{50} was 17 mm or smaller (Bunte and MacDonald, 2002). This distance is the default value for this sub-model, but users can input their own estimate for the mean annual travel distance. Once the mean annual travel distance has been specified, coarse sediment from a given arc is annually routed to the next arc that is the mean annual travel distance downstream. This sediment is stored in the stream arc and transported further downstream during the next year. The amount of sediment that reaches the watershed outlet is calculated annually. If the longest stream length through the watershed is shorter than the mean annual travel distance, the annual bedload sediment yield is equal to the sum of the coarse sediment delivered to the stream arcs. The output from FOREST is a spreadsheet listing bedload sediment yield for each watershed for each year simulated.

2.4.7.2 Bagnold's method for bedload transport

Although Bagnold's (1980) equation is one of the more accurate and used in other models (e.g., WARSSS: http://www.epa.gov/warsss/; SWAT: http://www.brc.tamus.edu/swat/index.html), it has been criticized because a limited dataset was used for calibration and the equation is not dimensionally balanced (Martin and Church, 2000). Martin and Church (2000) also found that excess stream power accounted for 66% of the variability in 247 bedload transport observations. After parameterizing and testing several variations of Bagnold's stream power equation, Martin and Church (2000) found that the most accurate equation was:

$$i_b = 8.40 * 10^{-5} + 7.93 * 10^{-2} * (\omega - \omega_0)^{3/2} * D_{50}^{1/4} \big/ d \qquad (2.14)$$

where i_b is the sediment transport rate per unit width of channel (kg m^{-1} s^{-1}), ω - ω_0 is the excess stream power, D_{50} is the median particle size (m), and d is the stream depth (m) (Table IV, Martin and Church, 2000). Because of its simplicity and relative accuracy (r^2 = 0.90; standard error of estimation = 0.22), Equation 2.14 is the basis for the other sub-model for predicting bedload sediment transport in FOREST for each stream arc.

Equation 2.14 requires that users calculate stream power:

$$\omega = \gamma QS / w \qquad (2.15)$$

where γ is the specific weight of water, Q is bankfull discharge (m^3 s^{-1}), S is the energy gradient of the water surface (m m^{-1}), and w is the stream width (m). If Equations 2.14 and 2.15 are to be used in a spatially explicit model, the user has to know flow depth, width, and discharge at numerous stream cross-sections over time. In most CWE assessments these data will not be available. In the absence of these data, other GIS applications have used using watershed area (A) to calculate bankfull discharge (Q) (Equation 2.16) (e.g., Gomez, 1991; Lane *et al.*, 1997). Similarly, empirical hydraulic geometry relationships have been used to calculate stream depth (d) and stream width (w) at different discharges (Equations 2.17, 2.18) (Leopold and Maddock, 1953; Finlayson and Montgomery, 2003):

$$Q = aA^b \qquad (2.16)$$

$$d = cQ^f \qquad (2.17)$$

$$w = gQ^h \qquad (2.18)$$

In these equations *a, b, c, f, g,* and *h* are empirical coefficients with values that can be found in the literature (e.g., Park, 1977; Dunne and Leopold, 1978; Knighton *et al.*, 1989; Lawlor, 2004; Keaton *et al.*, 2005; Westergard *et al.*, 2005). Most of these studies report values of *a, b, c, f, g,* and *h* in U.S. customary units and the values are used in these units as inputs into FOREST. This means that routines had to be written into FOREST that convert the GIS values for contributing area from square meters to square miles, and then use these values to calculate bankfull discharge in cubic feet per second (equation 2.16), plus depth and width in feet according to equations 22.17 and 2.18, respectively. Once these calculations are completed FOREST converts the discharge back to cubic meters per second and the depth and width to meters.

The flow depth at bankfull discharge also can be taken from a field within the attribute table of the stream GIS layer or simply assigned a value. Similarly, flow width can be taken from a field within the attribute table of the GIS layer or assigned a value. *S* is assumed to be equal to the streambed gradient and is automatically calculated from the DEM for each stream arc.

The same disturbances that increase erosion and sediment yield also can increase discharge. Any increase in discharge will increase stream depth and stream power, which in turn will increase downstream sediment transport. The changes in the 1st and 50th percentile flows are assumed to have a negligible effect on bedload transport while a change in the 99th percentile flows could substantially alter bedload transport. FOREST allows the user to account for a change in the 99th percentile flow by importing the predicted change in decimal percent (*%DQR99*) from Delta-QR. Equation 2.16 is then revised to:

$$Q = aA^b\,(1 + \%DQR99) \qquad (2.19)$$

and the revised discharge is automatically used in Equations 2.14 and 2.15.

The critical stream power (ω_0) is the amount of stream power needed to entrain sediment, and this depends mainly on the size of the particles on the streambed (Knighton, 1989). In general, the sands, silts, and clays being delivered from forest harvest, roads, and fires are likely to be finer than the particles that comprise the streambed. A selective entrainment of the finer particles means that the sediment being delivered from the different disturbances will be preferentially transported relative to the existing bed material. Hence FOREST assumes that the effective stream power (ω - ω_0) will preferentially transport the sediment being delivered from hillslopes and roads. FOREST provides users with two methods to calculate ω_0: 1) Bagnold's (1980) original equation with Shields' threshold criterion; or 2) Ferguson's (2005) method. These two methods are explained below, and the user can choose either method in accordance with the available data and their preferred assumptions.

The first method assumes a value of 0.04 for Shields' threshold criterion (Bagnold, 1980) in order to calculate ω_0 in steady state flow (Equation 2.20):

$$\omega_0 = 290D^{\frac{3}{2}} \log_{10}(\frac{12d}{D}) \qquad (2.20)$$

where D is the D_{50} of the stream bed (m) and d is the depth (m). This equation is appropriate for streambeds with a unimodal particle-size distribution (Bagnold, 1980). Users can input the D_{50} of the bed material or use the default value of 1.03 mm, as this is the mean of 0.062 mm and 2 mm, which represent the range of coarse sediment particle sizes. Similarly, users can input the stream depth or FOREST will calculate this for each stream arc using Equation 2.17.

The second method follows Ferguson's (2005) argument that one needs both the median particle size of the entrained sediment (D_i) and the median particle size of the streambed surface (D_b) to accurately predict the critical threshold of stream power. Following this logic Ferguson developed Equation 2.21:

$$\omega_0 = 0.104 * \left(\frac{D_b^{1.5}}{S^{0.17}} \right) * \left(\frac{D_i}{D_b} \right)^{0.67} \qquad (2.21)$$

This uses D_i, D_b, and S, but does not require stream depth. If the user selects Equation 2.21, D_i and D_b can be input by the user, or the user can assume that the input of sand-sized sediment dominates the streambed so D_b will equal D_i. The D_{50} required for Equation 2.14 can be either input by the user, or FOREST will assume the default value of 1.03 mm as explained previously.

The bedload transport rate per unit width of channel is calculated for bankfull discharge (Equation 2.14), and this rate is used as the annual transport capacity for each stream arc. Bankfull discharge is the channel forming flow that occurs on average every 1.5 years (Dunne and Leopold, 1978). Users must input the number of hours of channel forming flows in each watershed to convert the bedload transport rate in kg m^{-1} s^{-1} to kg m^{-1} yr^{-1} or they can use the default value of 16 hours. The bedload transport rate is multiplied by the spatially explicit stream width to calculate the absolute amount of bedload transport in kg yr^{-1}. Users can account for wet or dry years by simply changing the numbers of hours that channel forming flows occur.

FOREST calculates the annual supply of coarse sediment to each stream arc by adding the coarse sediment delivered from hillslopes and roads to the coarse sediment transported into that arc from upstream reaches. If the sediment supply is less than the transport capacity, all of the coarse sediment is routed to the next arc downstream and will be considered for transport in the same year. If the sediment supply is greater than the transport capacity, the amount of sediment routed downstream is determined by the transport capacity, sediment will accumulate at that arc, and be considered for transport the next year. The output from the bedload transport sub-model is a spreadsheet of the annual bedload sediment yield from each watershed for each year being simulated.

2.5 Graphical user interface, GIS, and programming languages

One of the main objectives for Delta-Q and FOREST was to implement an easy-to-use and consistent graphical user interface (GUI). The GUI was designed to facilitate simple, streamlined data input and to allow continuous execution of the FOREST sub-models from hillslope sediment production through watershed sediment yields. The GUI was written in Visual Basic to create a "Windows"-type environment and an example of a dialog box is shown in Figure 2.8.

Command buttons are used to open dialog boxes (Figure 2.8b), initiate calculations (Figure 2.8c), return the user to a previous menu (Figure 2.8d), or show online help files (Figure 2.8e). Default values are given for most parameters and the window environment allows these to be easily modified by the user (Figure 2.8f). Some inputs are disabled until a certain option is selected (Figure 2.8g).

FOREST has a parameter file routine to allow the user to save and quickly re-load many of the model inputs. The parameter file saves the names and details of the base GIS layers and other values input by the user (Figure 2.8a). This allows users to shutdown and re-start FOREST as necessary or easily compare different management scenarios. The interface is designed such that when users return to a simulation, they are prompted to select the directory where the simulation was run and FOREST automatically finds the parameter file. FOREST also reads the parameter file during the sediment delivery and routing sub-models so that the user does not have to re-enter inputs at different stages. The automated exchanges between sub-models means that the calculations in each sub-model are independent of other sub-models but successive calculations are seamless for the user. This design enables each sub-model to be easily updated and new sub-models to be added.

The code underlying the Visual Basic GUI is written in AML, ArcObjects, and Python languages; multiple languages were needed for the GUI, GIS, and custom functionality. Each code module interfaces seamlessly with the GUI so that the user is not aware of language changes or function changes from GIS to non-spatial tasks or calculations. Delta-Q and FOREST are coupled as stand-alone software but they require an ESRI® license to run the underlying GIS functionality.

2.6 Model verification and testing

A critical component of model development is verifying that the internal logic of the programs is consistent with the model equations and that the model functions as intended. Verification of CWE models such as Delta-Q and FOREST should test examples where a broad range of disturbances are simulated over space and time. The purpose of this section is to present the verification of Delta-Q and FOREST conducted for three watersheds in the Eldorado National Forest (ENF) in the central Sierra Nevada mountains of California (Figure 2.9). This section also will illustrate how model outputs can help land managers test assumptions and identify key concerns. Once a model has been verified, the model should be evaluated by comparing predicted and measured values to assess the predictive capability of the model, and this material is presented in Chapter 3.

2.6.1 Watershed descriptions

The three watersheds selected for model verification are the Dogtown (26 km^2), Dry Creek (13 km^2) and Steely (9 km^2) watersheds (Figure 2.9). The watersheds are all underlain by a granitic batholith and the andesitic Mehrten Formation, which was formed from mud and lava flows (USDA, 1986). Glaciation occurred below 1455 m on the western slope leaving areas of till and outwash material (USDA, 1986). Bedrock is overlain by fluvial deposits, glacial deposits, and volcanic debris. Soils are generally deep and well drained (USDA, 1986). Elevations in the watersheds range from 1240 to 1855 m. The mean slope for the watersheds is 26%, but in the inner gorge areas slopes can reach 100%. Stream densities are 2.2 km km^{-2} for Dogtown, 2.3 km km^{-2} for Dry Creek, and 2.3 km km^{-2} for Steely.

The ENF has a Mediterranean-type climate with wet winters and warm dry summers. The climate is influenced by the high elevations of the Sierra Nevada range and moist Pacific air masses from the west. The mean annual precipitation is 1230 mm, but annual values can range from 450 to 2310 mm (USDA, 1986). Ninety-five percent of the precipitation occurs between November and April. Above 1500 m the precipitation falls mostly as snow and below 1500 m the precipitation is mostly rain (USDA, 1986).

In the absence of any disturbance, forested areas are dominated by white fir (*Abies concolor*), red fir (*Abies magnifica*), sugar pine (*Pinus lambertiana*), and Jeffrey pine (*Pinus jeffreyi*) with lodgepole pine (*Pinus contorta*) at higher elevations (USDA, 1986). Understory shrubs include greenleaf manzanita (*Arctostaphylos patula*), huckleberry oak (*Quercus vaccinfolia*), and mountain whitethorn (*Ceanothus cordulatus*).

The main disturbances in the three watersheds that contribute to hydrologic and sedimentary CWE are roads, timber harvest, and wildfires (Table 2.3). Until the early 1990's, timber harvest was typically accomplished by either clearcutting or thinning (Figure 2.10a). In 1993 the California Spotted Owl (CASPO) thinning rules specified that no tree greater than 76 cm could be harvested and that 40% of the canopy cover must remain after harvest; for verification areas harvested under these rules were treated the same as areas subjected to thinning. Dogtown was subjected to small and frequent clearcuts from 1981 to 2000 while Dry Creek was extensively thinned (Figure 2.10). Timber harvest in the Steely watershed was primarily by clearcutting but this was less extensive than in Dogtown.

The burned areas were classified by burn severity following Wells *et al.* (Figure 2.10b) (1979). High severity fires burn all of the litter, and alter the color and structure of the surface mineral soil. Moderate severity fires consume most of the soil organic material but do not alter the mineral soil. A low severity fire will only scorch or partially burn the organic material (Wells *et al.*, 1979). High and moderate severity wildfires have occurred in Dry Creek and Steely watersheds (Figure 2.10b, Table 2.4). In some cases the actual timing and magnitude of the disturbances were altered in order to test fully every aspect of the models; hence data from this case study should not be used as a prediction of actual CWE for these watersheds.

2.6.2 Delta-Q inputs

Delta-Q was used to calculate the percent change in 99th percentile flows from 1970 to 2010. GIS layers for timber harvest and fire contained information about the type of timber harvest and fire severity, respectively, and the year of each disturbance. For each type of timber harvest and fire severity users must specify an initial change in flow (DQ) and the number of years to hydrologic recovery. The values for clearcuts were chosen from the online help values listed for clearcut watersheds with similar elevations and mean annual precipitation (Table 2.5). The initial DQ for thinning and CASPO thins were assumed to be half of the DQ value for clearcuts, and the years to hydrologic recovery were reduced from 20 to 15 (Table 2.5).

The initial DQ for high severity fires was twice the DQ for clearcuts since soil water repellency and soil sealing typically increase runoff after high severity fires (DeBano, 1981; Larsen *et al.*, in press); the years to recovery was set to 20 as this is approximately the time needed for interception and transpiration to return to pre-fire values (MacDonald and Stednick, 2003). The DQ values for moderate and low severity fires were assumed to be one half and one quarter, respectively, of high severity fires; similarly, times to recovery were decreased to 15 years and 5 years, respectively.

2.6.3 FOREST inputs

FOREST simulations were run from 1970 to 2010 for the same timber harvest and fire severity layers that were used in Delta-Q. The background rate for sediment production was set to the default value of 0.01 Mg ha^{-1} yr^{-1}. An initial hillslope sediment production value of 0.224 Mg ha^{-1} yr^{-1} and a six year recovery period were selected using the online help files for clearcut areas (Table 2.6). The sediment production rates for both types of thinning were half of the value used for clearcuts. Based on values from the online help, the initial sediment production rate for high severity fires was 12 Mg ha^{-1} yr^{-1} (Table 2.6). The value for moderate severity fires was selected to be 2.4 Mg ha^{-1} yr^{-1} or one-fifth of the value for high severity fire. For low severity fires, sediment production values were 1.2 Mg ha^{-1} yr^{-1} or one-tenth of the value for high severity fires. The time to recovery was set to five, three, and two years for high, moderate and low severity fires respectively, based on field studies in California (Chase, 2005) and the Colorado Front Range (Pietraszek, 2006).

The hillslope sediment delivery sub-model in FOREST requires that each disturbance type is matched to one of the seven land management or cover types in the look-up tables (Table 2.1). Clearcut areas were assumed to be similar to low severity fires; thinned areas were assumed to be similar to a five-year old forest. High and low severity fire are cover types in the look-up table; areas burned at moderate and low severity were set to low severity as there is no land cover type for moderate severity fire in Disturbed WEPP.

The cell size in FOREST was set to 10 m since this was the cell size of the input DEM. The same cell size and DEM were used for the output rasters so that all rasters were congruent. The maximum stream arc length was set to 500 m.

A new local climate file was generated for the three watersheds using Rock: Clime, which is the stochastic weather generator developed by the U.S.F.S. Rocky Mountain Research Station (http://forest.moscowfsl.wsu.edu/cgi-bin/fswepp/rc/rockclim.pl). The new climate was based on the weather station at Tahoe, CA, and adjusted for location and elevation using the PRISM database. The PRISM database has elevation and monthly precipitation values for a 4-km raster layer covering the continental U.S. The parameters for the new climate were used to create a 100-year stochastic weather record. These weather data were used with WEPP for windows to create a new look-up table of sediment delivery values for each combination of hillslope gradient, land cover, downslope land cover, and soil type as described in section 2.3.

Road sediment production was calculated for each road arc using the equation developed by Coe (2006), as this was developed from data collected on the Eldorado National Forest. The total storm erosivity was set to 1021 MJ mm ha^{-1} h^{-1} $year^{-1}$ (60 hundreds of foot * tonf * inch $acre^{-1}$ yr^{-1}) using the online isoerodent map for California (Renard *et al.*, 1997). The road GIS layer was used as an input and the average road width was set to 4 m (Coe, 2006). Road arc lengths were shortened to a maximum of 200 m and the gradient of each road arc was calculated in FOREST. Selected road segments were specified as recently graded in order to ensure that this factor was being correctly calculated by FOREST. The road sediment delivery buffer width was calculated to be 50 m using equation 2.11 and mean annual precipitation of 1230 mm. Hillslope and road sediment delivery were separated into fine (<0.062 mm) and coarse (0.062 to 2 mm) components based on the locations of clay and silt loam soils versus sandy loam soils in the soil texture raster.

As described in section 2.3, the fine sediment was routed to the watershed outlet in the same year that it was delivered to the stream. The coarse sediment was routed using the default value of 2400 m for the mean annual travel distance (MATD). The coarse sediment was then routed using Martin and Church's parameterization of Bagnold's equation (Equation 2.14) in order to compare the results of these two bedload routing procedures.

The input values for Bagnold's method are listed in Table 2.7. The hydraulic geometry coefficients (a, b, c) and exponents (f, g, h) were taken from an analysis of 41 sites in western Montana where the mean annual precipitation was greater than 1140 mm (Lawlor, 2004). Critical stream power was calculated using Equation 2.20 and the bedload sediment particle size (D_{50}) was set to 1.03 mm.

2.6.4 Results

The three watersheds all show a similar pattern with respect to the predicted changes in the 99th percentile flow, but the magnitude varied with the amount and types of disturbances (Figure 2.11a). For Dogtown watershed the maximum change in flow was 2.6% in 1990, and this was mainly due to clearcutting on 23% of the watershed in 1989. The maximum change in flow for Dry Creek was estimated to be 16% or six times larger than in Dogtown, as a high severity fire burned 33% of the watershed in 1987 (Figure 2.11b). The maximum change in flow on Steely watershed was 10% in 1987, with fire accounting for 8.5% of the change in flow and timber harvest accounting for the remaining 1.5% (Figure 2.11c). The changes in the 99th percentile flows illustrate the linear hydrologic recovery after each disturbance but the recovery curves for Dogtown and Dry Creek are more complex due to the small increases as additional timber harvest occurred. From 2000 to 2010 the recovery curves are smooth because there were no new disturbances in the data used for the simulations.

Maps of the predicted hillslope sediment production and delivery are shown for each watershed for 1987, 1989, 1991, and 1993 (Figure 2.12). These show the dominant effect of the 1987 fire in the Dry Creek and Steely watersheds as the initial sediment production rates were up to 12 Mg ha^{-1} yr^{-1} (Figures 2.12). The high sediment production rates resulted in high initial sediment delivery rates to the downslope stream arcs, and then a relatively rapid decline as the hillslopes recover (Figure 2.12).

Plots of the hillslope sediment production rates over time show the largest increases in Dry Creek and Steely watersheds due to the high severity fires in these two watersheds (Figure 2.13). The maximum sediment production rate normalized by watershed area was

398 Mg km^{-2} yr^{-1} for Dry Creek and 233 Mg km^{-2} yr^{-1} for Steely but only 14 Mg km^{-2} yr^{-1} for Dogtown as the primary disturbance was timber harvest. As with the change in flow, the decline in sediment production over time was rapid and largely linear as the small areas of thinning and CASPO thinning in Dry Creek and Steely watersheds had relatively little effect on hillslope sediment production (Figure 2.13).

In Dogtown, the total sediment production over time was more complex in Dogtown as timber was harvested periodically from 1981 to 2000. The highest sediment production rate was 14 Mg km^{-2} yr^{-1} in 1989 after the largest clearcut of 2.6 km^2 (Figure 2.13). The assumed recovery periods mean that sediment production rates declined to background levels by 1993 in the Dry Creek and Steely watersheds and by 1998 in Dogtown watershed (Figure 2.13).

The predicted amounts of sediment delivered to streams are much larger per unit area for Dry Creek and Steely than Dogtown, and this indicates the dominance of the high severity fires relative to timber harvest (Figure 2.14). Sediment delivery curves for all three watersheds exhibit the similar temporal pattern of peak, minimum, and recovery to background rates after disturbance. In the Steely watershed 97% of the sediment produced was predicted to reach the stream channels, and this proportion is higher than for the other watersheds. The main reason for this difference is that the fires in Steely occurred closer to the streams whereas in Dry Creek more ridgetop areas were burned. Nevertheless, 92% of the sediment that was produced in Dry Creek was delivered to the streams. In Dogtown only 79% of the sediment produced was delivered to the streams, and this is because clearcuts had a lower sediment delivery rate than high severity fires. The patterns of delivered fine- and coarse-textured sediment were similar as they are a consistent proportion of the total sediment delivered (Figure 2.14a; section 2.4.3).

In Dogtown the amount of sediment delivered dropped below the background rate 3-4 years after the main clearcut (Figure 2.14a). Further investigation showed that this result was due to the assumed sequence of vegetative recovery from low severity fire (representing a clearcut) back to a 20-year old forest. It turns out that the WEPP model assumes a lower percent sediment delivery rate for tall and short grasses than for a 5- and 20-tear old forest. The validity of this reduction below the background rate is debatable since a mature forest is generally assumed to have a high infiltration rate, little or no surface runoff, and very little sediment delivery from sheetwash, rilling, and gullying (ref?). The same effect occurred in the other two watersheds, but the relative magnitude was much smaller because the very large amounts of sediment generated by high-severity fires relative to timber harvest.

The mean road sediment production rates ranged from 2.5 to 2.8 Mg km^{-1} yr^{-1} (Table 2.8). The small variability between watersheds was due to the similar road densities, road widths, climate, and soils. However, values for individual road arcs ranged up to 3.9 kg m^{-1} yr^{-1} (Figure 2.15a). Dogtown roads delivered the most sediment (16 Mg coarse; 48 Mg fine) in absolute terms since there were more roads in this watershed (Table 2.8). Dry Creek had the highest proportion of roads that were connected or closest to streams and the highest proportion of sediment that was delivered at 39% (Table 2.8). Dogtown and Steely delivered 30% and 36% respectively, of sediment produced (Table 2.8) as fewer roads in these watersheds were closer to the streams and roads were in general less steep.

The annual suspended sediment yield in each watershed is the sum of the fine sediment delivered from hillslopes and roads as FOREST assumes that all of the fine sediment is routed through the stream network in the same year in which it is delivered. The overall temporal pattern of suspended sediment yields is similar to the temporal pattern of sediment production because most of the sediment produced from the hillslopes was delivered to the streams, and the roads accounted for only a small percentage of the total sediment yields. The predicted suspended sediment yields were dominated by the 1987 fires, and the highest values were 278 Mg km^{-2} yr^{-1} in 1987 in Dry Creek and 172 Mg km^{-2} yr^{-1} in Steely (Figure 2.16). The maximum suspended sediment yield in Dogtown was only 10 Mg km^{-2} yr^{-1} (Figure 2.16) because timber harvest produced so much less sediment than the high severity fires (Table 2.6).

The predicted routing of bedload sediment using the default MATD of 2400 m was delayed relative to the suspended sediment. At the beginning of each simulation, three to six years were required before the undisturbed sediment yields stabilized and this depended on the maximum stream length in each watershed (Table 2.9; Figure 2.17a). Peak sediment yields were highest in Dry Creek at 87 Mg km^{-2} yr^{-1} compared to the maximum values of 49 and 3.4 Mg km^{-2} yr^{-1} in Steely and Dogtown watersheds, respectively. The time to peak bedload sediment yield was faster in Steely as the fire was within two km of the watershed outlet (Figure 2.17a). In contrast, the time to peak bedload sediment yield in the Dry Creek watershed was two years after the 1987 fires because the burned areas were 4.7 km upstream of the watershed outlet (Table 2.9). Similarly, the time to peak bedload sediment yield for Dogtown was delayed for three years after the peak hillslope sediment delivery values because the 1987 and 1988 clearcuts were nearly five km upstream of the watershed outlet (Table 2.9). These variations in the timing of peak sediment yields help verify that the MATD sub-model is functioning correctly.

Bedload sediment yields calculated using Bagnold's equation showed differences in magnitude and timing from the MATD sediment yields (Figure 2.17). The peak bedload sediment yield at Dry Creek increased from 87 to 93 Mg km-2 yr-1 and this occurred two years earlier than the peak calculated using the MATD method. The larger and faster peak at Dry Creek occurred because the calculated stream power was so much larger than the critical stream power. This meant that all of the coarse sediment was transported through the stream channel each year instead of being stored. At the Steely watershed the peak yield increased from 49 to 58 Mg km^{-2} yr^{-1} and occurred the same year regardless o the routing procedure. The similar timing for both methods happened because the stream length was less than 2400 m and the stream power was again much larger than the critical stream power (Figure 2.17).

The predicted peak bedload sediment yield at Dogtown did not change between the different bedload routing procedures, but the peak occurred two years earlier using the Bagnold procedure than with the MATD (Figure 2.17). Again the earlier peak was due to the excess of calculated stream power relative to the critical stream power and the stream lengths being longer than 2400 m Bedload sediment yields were more spread out over time in Dogtown because the disturbances occurred over a longer time period and were more scattered in space than the high severity fires that dominated sediment yields in the other two watersheds.

2.7 Discussion

2.7.1 Potential uses of Delta-Q and FOREST

The results indicate that Delta-Q and FOREST are useful because of their ability to spatially and temporally model different land use histories and projected management scenarios. Users of other models such as GEOWEPP are expected to model each year separately by explicitly assigning changes to vegetation and soil inputs as necessary and re-running the simulations. The effect of different recovery rates on hydrologic and sedimentary CWE can be evaluated in Delta-Q and FOREST because of the ease of simulating several years and the land cover changes over time. Similarly, the models readily allow users to assess the effect of varying the recovery rate on CWE. FOREST also generates GIS layers at each stage of calculations, and these provide a visualization of the spatially distributed values for sediment production, delivery and routing over time (Figures 2.12, 2.15). These allow users to readily determine which stream reaches have the greatest risk for sedimentation over time. Users also can use these GIS layers to map sediment source areas from past management actions and to compare future management scenarios.

The quantitative results for the watersheds being simulated are saved in text files and displayed in spreadsheets. The user can create different GIS inputs of proposed management scenarios to use in FOREST and compare output layers to minimize CWE. The summary results can be graphed for comparisons of different proposed scenarios.

Users can adjust several model parameters to simulate different scenarios for planning or analysis. For example, the initial changes in flow and sediment production or recovery time periods can be adjusted higher or lower than for average years. Users can adjust for wet or dry years by altering the climate files in Rock Clime. Altering the climate files will affect percent sediment delivered values in the look-up tables created using WEPP simulations and using these tables in FOREST will show the how sediment delivery and yields are affected by the change in climate. Users also can evaluate the effect of changing the mean annual precipitation on road sediment delivery. The potential for evaluating the effects of changing parameters is another practical benefit for users who need to assess the CWE of management scenarios.

2.7.2 Limitations on modeling CWE

The implementation of spatially explicit models has been limited by: 1) computer technology, 2) the lack of data to model CWE, and 3) the lack of proven algorithms to accurately describe the various watershed processes that result in a CWE. As computer processing speeds continue to increase it will become much more feasible to use spatially explicit models such as Delta-Q and FOREST to assess the effect of multiple planning scenarios on the development of CWE.

The amount of spatial data for running CWE models has greatly increased in recent years through the use of remote sensing techniques, GPS, and GIS. DEMs, soils, stream, roads, land use and cover layers are freely available online and provide full coverage for the US; these data greatly facilitate spatially-explicit modeling. The greater limitation is that field data remain expensive and labor intensive to collect. Such data are essential for creating empirical models, and to parameterize and validate existing models. Existing data are particularly limited given the tremendous variability in watershed processes, climates, and responses to different types of disturbances. Long term data sets are especially valuable to capture the variations in climate, and the lack of such data also hinders our ability to determine valid recovery coefficients.

One of the modeling objectives of this research was to use existing algorithms but in some cases these were not available. For hillslope sediment delivery it was necessary to rely on data derived from other models, such as WEPP and Rock:Clime. Road sediment production is currently predicted using published empirical models, but production rates also could be derived from models such as Road:WEPP (Elliot, 2004) and SEDMODL2 (NCASI, 2003). Although these supplementary models are not explicitly coupled to FOREST, changes in these models could alter the results predicted by FOREST, and this may limit the comparability of results predicted at different times using FOREST. This is why a modular approach was used for FOREST, as this allows new models and changes in existing models to be easily incorporated into FOREST.

2.7.3 Limitations of Delta-Q and FOREST

Models by definition are limited abstractions of reality and they perform best when applied to the specific situations for which they are designed. Delta-Q and FOREST were designed to calculate the hydrologic and sedimentary CWE due to forest harvest, roads, and fires, but there are some conditions for which these models should not be used. The models also are designed to predict mean annual changes, but the severity of CWE will vary with the interannual variations in climate. The purpose of this section is to identify some of the specific conditions or issues where the use of Delta-Q and FOREST may not be appropriate, and the trade-offs between the use of climatic means versus a more stochastic approach.

Delta-Q and FOREST do not account explicitly for mass movements, bed and bank erosion, or extreme climatic events. However, mass movements that are not induced by management activities are implicitly accounted for in the long-term background sediment production rate (Riebe *et al.*, 2000). In areas where mass movements are not common or the size and frequency of mass movements are not altered by management actions, Delta-Q and FOREST should be applicable. The models should not be used for assessing CWE when the frequency or magnitude of mass movements will be altered by the proposed management activities. Similarly, FOREST does not consider bed and bank erosion, so FOREST should not be used to assess CWE if bed and bank erosion is a major sediment source. It should be noted that FOREST was designed for small forested watersheds where hillslope processes are more likely to dominate sediment production and delivery (Lane *et al,* 1997).

Both models predict CWE based on mean conditions. A stochastic approach also could be used, and in this case probability density functions (PDFs) would be needed to represent the frequencies and magnitudes of an event and/or watershed characteristics. Multiple runs of these models using parameter values selected from the PDF would then yield a PDF of potential outcomes. This approach is useful given the unpredictability of future events (e.g., Benda and Dunne, 1997a, 1997b; Gabet and Dunne, 2003), but stochastic models have rarely been used to assess or predict CWE for several reasons. First, the data needed to create a locally applicable PDF are rarely available. Second, PDFs require many model runs to determine the probability of outcomes. Despite advances in computing power the sheer number of calculations means that a stochastic version of FOREST could take several days to run and this would be too time-consuming for management purposes. Finally, the GUI for Delta-Q and FOREST was designed to accept inputs in a logical, step-by-step fashion so that the user is aware of each calculation and results before proceeding to the next sub-model. A stochastic approach would require the GUI to be redesigned for batching model runs in order to simulate the variations in climate or watershed characteristics, and this would substantially complicate the model inputs and user interface.

2.7.4 Research needs and model additions

The process of model development and testing resulted in the identification of a number of potential improvements and additions to Delta-Q and FOREST as well as research needs. One of the most important additions to FOREST would be a more detailed procedure for predicting road sediment production and delivery, as roads are often the largest source of sediment in forested watersheds (Megahan, 1972; Sun and McNulty, 1998, Croke *et al.*, 1999). Road sediment production and delivery rates vary considerably with road design, so FOREST could be improved by adding a module that could account for the effects of insloped versus outsloped roads. The ability to predict road sediment delivery would be markedly increased by having data on the location of culverts and road drainage points, and many national forests are now trying to collect and archive such data using global positioning systems and high resolution DEMs. Modeling accuracy also could be improved by having a timeline of road construction and grading, as this can greatly affect road sediment production and delivery rates (Coe, 2006; Stafford and MacDonald, 2008; Stafford and MacDonald, 2009).

The prediction of hillslope sediment delivery could be improved with the use of high resolution DEMs. In many areas fires may be the largest source of sediment (Section 2.5.4), and hillslope convergence is a key control on the concentration of overland flow. Rill, gully, and channel erosion are the primary sources of post-fire erosion and sediment delivery (Pietraszek, 2006). The availability of surface roughness data such as slash, litter, and ground vegetation also could improve the predicted hillslope sediment delivery (Rivenbark and Jackson, 2004) but more research is needed to quantify the effects of these data.

FOREST also could be improved by adding one or more sub-models to estimate bed and bank erosion. This would help make FOREST more applicable for larger watersheds where CWE may be an even greater concern. However, the complexity of such sub-models, together with the interactions between peak flows, channel morphology, and sediment yields, may be incompatible with the initial objectives for FOREST.

2.8 Conclusions

Cumulative watershed effects (CWE) are a pervasive problem and their analysis and prediction are highly complex. A wide range of tools are available to assess the CWE resulting from management activities, and these vary in their data needs, outputs, and skills required (Reid, 1993; Merritt *et al.*, 2003, Elliot *et al.*, 2006). Existing CWE tools tend to be either too simple and not scientifically based, or too complex and require large amounts of data that are simply not available for the forested watersheds that are the focus of this research.

This project developed two models to help predict hydrologic and sedimentary CWE in a spatially and temporally explicit manner. The modeling objective was to provide easy-to-use, scientifically based tools for land managers who need to: 1) assess current CWE due to roads, timber harvest, and fires; and 2) predict and compare the CWE of proposed management activities. Delta-Q calculates absolute or relative changes in flow after forest disturbances. FOREST calculates sediment production and delivery to streams from hillslopes and roads, and sediment routing in streams.

Both models are comprised of coupled empirical and conceptual sub-models along with a windows-based graphicl user interface (GUI) that facilitates step-by-step data input.

The GUI and GIS calculations are seamlessly interfaced so that the user is not affected by the underlying changes in programming languages or software. The automatic creation of a parameter file in FOREST means that users can quickly and easily run a series of simulations or re-start a given sub-model. Programming is modular so updated sub-models can be included in the GUI.

Model assumptions and limitations have been made explicit, but users should have some basic knowledge of hydrology. The models do not account for landslides and other stochastic events, nor do they account for bed and bank erosion.

Outputs for Delta-Q include spreadsheets with annual values of changes in flow, while the outputs for FOREST include spreadsheets with total sediment production, delivery and yields for each watershed modeled. The models also generate GIS layers for hillslope sediment production; add road sediment production to the roads layer; and add sediment delivery to each arc in the stream layer. The spatially explicit results can be used to immediately visualize hotspots of sediment production and delivery, and identify stream reaches at risk for CWE.

The models were verified by a case study of three watersheds on the Eldorado National Forest in California. This showed that the models functioned as planned and provided reasonable results. Model runs were repeatable and consistent for different disturbances. In two of the watersheds, the changes in flow and sediment yields were primarily due to high severity wildfires. In the third watershed most of the disturbance was due to clearcutting and thinning, and the predicted changes in runoff and sediment yields were much less than for the two watersheds where burning was the primary source of disturbance. The results of the case study confirm the usefulness of the models for quantifying and comparing CWE, as well as identifying locations of particular concern.

2.9 References

Allan, J.D., 1995. *Stream ecology: structure and function of running waters.* Chapman and Hall, New York, NY, 388 pp.

ArcGeoWEPP for ArcGIS v.9.x. http://www.geog.buffalo.edu/~rensch/geowepp/beta/. Accessed 2006.

Austin, S.A., 1999. Streamflow response to forest management: a meta-analysis using published data and flow duration curves, Colorado State University, Fort Collins, Colorado, 265 pp.

Bagnold, R., 1980. An empirical correlation of bedload transport rates in flumes and natural rivers. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, p. 453-473.

Baker, M., 1986. Effects of ponderosa pine treatments on water yield in Arizona. *Water Resources Research* 22(1): 67-73.

Beasley, D.B. and Huggins, L.F., 1982. ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation): User's Manual, U.S. Environmental Protection Agency, Chicago, Illinois.

Beaty, K. G., 1994. Sediment transport in a small stream following 2 successive forest-fires. *Canadian Journal of Fisheries and Aquatic Sciences* 51(12): 2723-2733.

Benavides-Solorio, J., 2003. Post-fire runoff and erosion at the plot and hillslope scale, Colorado Front Range. Ph.D. dissertation, Colorado State University, Fort Collins, Colorado, 218 pp.

Benavides-Solorio, J., and L.H. MacDonald, 2005. Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range. *International Journal of Wildland Fire* 14:1-18.

Benda, L., and T. Dunne, 1997a. Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. *Water Resources Research* 33(12): 2849-2863.

Benda, L.E., and T. Dunne, 1997b. Stochastic forcing of sediment routing and storage in channel networks. *Water Resources Research* 33(12): 2865-2880.

Beschta, R.L., 1978. Long-term patterns of sediment production following road construction and logging in the Oregon Coastal Range. *Water Resources Research* 14(6): 1011-1016.

Borah, D.K., 2002. Watershed scale nonpoint source solution models: mathematical bases. Paper Number: 022091. ASAE Annual International Meeting, Chicago, Illinois, 16 pp.

Bosch, J.M., and J.D. Hewlett, 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55: 3-23.

Bravo-Espinosa, M., W.R. Osterkamp, and V.L. Lopes, 2003. Bedload transport in alluvial channels. *Journal of Hydraulic Engineering* 129(10): 783-795.

Bunte, K., and L.H. MacDonald, 1999. Scale considerations and the detectability of sedimentary cumulative watershed effects. Technical Bulletin No. 776, National Council for Air and Stream Improvement, Research Triangle Park, NC. 327 pp.

Bunte, K., and L.H. MacDonald, 2002. Predicting the mean annual travel distance of streambed particles: a meta-analysis of published data. *EOS Trans.* Abstract H21G-05, American Geophysical Union Fall Meet. Suppl., San Francisco, California.

Caminiti, J.E., 2004. Catchment modelling - a resource manager's perspective. *Environmental Modelling & Software* 19(11): 991-6.

Campbell, D.H. 1984. The transport of road derived sediment: a function of slope characteristics and time. M.S. thesis, Colorado State University, Fort Collins, Colorado, 46 pp.

Chase, E., 2005. Effect of salvage logging on post-fire sediment production rates on the Star Fire in the central Sierra Nevada, CA. M.S. thesis, Colorado State University, Fort Collins, Colorado, 81 pp. plus app.

Council on Environmental Quality (CEQ), 1997. Considering cumulative effects under the National Environmental Policy Act. Washington, D.C. 64 pp. plus app.

Cobourn, J., 1989. An application of cumulative watershed effects (CWE) analysis on the Eldorado National Forest in California. In *Proceedings of the Symposium on Headwaters Hydrology*, American Water Resources Association, Bethesda, MD, pp. 449-460.

Coe, D.B., 2006. Sediment production and delivery from forest management activities in the central Sierra Nevada, CA. M.S. thesis, Colorado State University, Fort Collins, Colorado, 117 pp.

Croke, J., Hairsine, P. and Fogarty, P., 1999. Sediment transport, redistribution and storage on logged forest hillslopes in south-eastern Australia. *Hydrological Processes* 13(17): 2705-2720.

Croke, J., and S. Mockler, 2001. Gully initiation and road-to-stream linkage in a forested catchment, southeastern Australia. *Earth Surface Processes and Landforms* 26: 205-217.

DeBano, L., 1981. Water repellent soils: a state of the art. USDA Forest Service GTR-PSW-046, Berkeley, California, 21 pp.

Dietrich, W.E, J. W. Kirchner, H. Ikeda, and F. Iseya, 1989. Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. *Nature* 340: 215-217.

Dingman, S.L., 2002. *Physical Hydrology*. Prentice Hall, New Jersey, 646 pp.

Distributed Hydrology Soils and Vegetation Model – DHSVM. http://www.hydro.washington.edu/Lettenmaier/Models/DHSVM/. Accessed 2005.

Duncan, S.H., R.E. Bilby, L.W. Ward, and J.T. Heffner, 1987. Transport of road surface sediment through ephemeral stream channels. *Water Resources Bulletin* 23(1): 113-119.

Dunne, T., and Leopold, L., 1978. *Water in environmental planning*. W. H. Freeman & Company, San Francisco, CA, 818 pp.

Elliot, W.J., 2004. WEPP internet interfaces for forest erosion prediction. *Journal of the American Water Resources Association* 42(2): 299-309.

Elliot, W.J., K. Hyde, L.H. MacDonald and J. McKean, 2006. Tools for analysis. In: W.J. Elliot, and Audin, L.J., (Eds.), DRAFT *Cumulative Watershed Effects of Fuels Management in the Western United States*. http://forest.moscowfsl.wsu.edu/engr/cwe/. Accessed November 2006.

Environmental Protection Agency (EPA), 2000. National Water Quality Inventory, 1998 report to Congress. http://www.epa.gov/305b/98report/. Accessed 5 May 2006.

Ferguson, R., 2005. Estimating critical stream power for bedload transport calculations in gravel-bed rivers. *Geomorphology* 70: 33-41.

Ferro, V., and P. Porto, 2000. Sediment delivery distributed (SEDD) model. *Journal of Hydrologic Engineering* **5**(4): 411-422.

Flanagan, D.C., and S.J. Livingstone (Editors), 1995. WEPP user summary. NSERL Report No. 11, National Soil Erosion Research Laboratory, West Lafayette, IN, 131 pp.

Finlayson, D.P., and D. R. Montgomery, 2003. Modeling large-scale fluvial erosion in geographic information systems. *Geomorphology* 53: 147-164.

Gabet, E.J. and Dunne, T., 2003. A stochastic sediment delivery model for a steep Mediterranean landscape. *Water Resources Research* 39(9): 1237-1249.

GeoWEPP for ArcView v.3.x. http://www.geog.buffalo.edu/~rensch/geowepp/. Accessed 2005.

Gomez, B., and M. Church, 1989. An assessment of bed load transport formulae for gravel-bed rivers. *Water Resources Research* 25(6): 1161-1186.

Gomez, B., 1991, Bedload transport. *Earth Science Reviews* 31: 89-132.

Johansen, M.P., T.E. Hakonson, and D.D. Breshears, 2001. Post-fire runoff and erosion from rainfall simulation: contrasting forests with shrublands and grasslands. *Hydrological Processes* 15: 2953-2963.

Jones,J., 2000. Hydrologic processes and peak discharge response to forest removal, regrowth and roads in 10 small experimental basins, western Cascades, Oregon. *Water Resources Research* 36(9): 2621-2642.

Keaton, J.N., T. Messinger, and E.J. Doheny, 2005. Development and analysis of regional curves for streams in the non-urban valley and ridge physiographic province, Maryland, Virginia, and West Virginia. US Geological Survey Scientific Investigation Report 2005-5076, 116 pp.

Ketcheson, G.L., and W.F. Megahan, 1996. Sediment production and downslope sediment transport from forest roads in granitic watersheds. Research Paper INT-RP-486. USDA Forest Service, Intermountain Research Station, Ogden, UT. 11 pp.

Kineros2. http://www.tucson.ars.ag.gov/kineros/. Accessed 2006.

Knighton, D., 1998. *Fluvial forms and processes*. Oxford University Press, New York, NY, 400 pp.

Knighton, M.D., R.M. Solomon, and S.S.Y. Wang, 1989. Applications and research in sediment delivery and routing models in the USDA Forest Service. International symposium on sediment transport modeling, American Society for Civil Engineering, New York.

Kreutzweiser, D.P., and S.S. Capell, 2001. Fine sediment deposition in streams after selective forest harvesting without riparian buffers. *Canadian Journal of Forest Research* 31(12): 2134-2142.

Lacey, S.T., 2000. Runoff and sediment attenuation by undisturbed and lightly disturbed forest buffers. *Water, Air, and Soil Pollution* 122(1-2): 121-138.

Lancaster, S.T., Hayes, S.K., Grant, G.E., and Anonymous, 2002. Modeling sediment and wood storage and dynamics in small mountainous watersheds. *Abstracts with Programs - Geological Society of America* 34(5): 89.

Lane, L.J., 1982. Development of a procedure to estimate runoff and sediment transport in ephemeral streams. *Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield.* IAHS Publication No. 137, p. 275-282.

Lane, L.J., M. Hernandez, and M. Nichols, 1997. Processes controlling sediment yield from watersheds as functions of spatial scale. *Environmental Modelling and Software* 12(4): 355-369.

Larsen, I.J., and L.H. MacDonald, 2007. Predicting postfire sediment yields at the hillslope scale: testing RUSLE and Disturbed WEPP. *Water Resources Research*, 43 (w11412, doi:10.1029/2006WR005560): 18 pp.

Larsen, I.J., and L.H. MacDonald, 2007. Does ash contribute to post-fire soil sealing and increased runoff rates? 27th Annual AGU Hydrology Days, Colorado State University, Fort Collins, CO.

Larsen, I.J., L.H. MacDonald, E. Brown, D. Rough, M.J. Welsh, J.H. Pietraszek, Z. Libohova, and K. Schaffrath, Benavides-Solorio, J., in press. Causes of post-fire runoff and erosion: the roles of soil water repellency, surface cover, and soil sealing. *Soil Science Society of America Journal*.

Lawlor, S., 2004. Determination of channel-morphology characteristics, bankfull discharge, and various design-peak discharges in Western Montana. US Geological Survey Scientific Investigation Report 2004-5263, 26 pp.

Leopold, L.B., and Thomas Maddock, Jr., 1953. The hydraulic geometry of stream channels and some physiographic implications. US Geological Survey professional paper 252, U.S. Govt. Print. Office, Washington, D.C., 53 pp.

Lewis, J., and Ziemer, R.R., 1998. Evaluating the impacts of logging activities on erosion and suspended sediment transport in the Caspar Creek watersheds. General Technical Report PSW-GTR-168. USDA Forest Service, Pacific South West Research Station, CA, p. 55-69.

Libohova, Z. 2004. Effects of thinning and a wildfire on sediment production rates, channel morphology, and water quality in the Upper South Platte watershed. M.S. thesis, Colorado State University**,** Fort Collins, Colorado, 103 pp.

Lisle, T.E., 1995. Particle size variations between bed load and bed material in natural gravel bed channels. *Water Resources Research* 31(4): 1107-1118.

Litschert, S.E., and L.H. MacDonald, 2004. Connectivity of timber harvest units to the stream network in the Sierra Nevada, California. *EOS Trans.* Abstract H51B-1124, American Geophysical Union Fall Meet. Suppl., San Francisco, California.

Lopes, V.L., P.F. Ffolliott, and M.B. Baker, Jr., 2001. Impacts of vegetative practices on suspended sediment from watersheds of Arizona. *Journal of Water Resources Planning and Management* 127(1): 41-47.

Luce, C. H., and T.A. Black, 1999. Sediment production from forest roads in western Oregon. *Water Resources Research* 35(8): 2561-2570.

Luce, C.H., and T.A. Black, 2000. Erosion over time from forest roads in the Oregon Coast Range. In: C.W. Slaughter (Editor), Water Resources Center Report 98, Centers for Water and Wildland Resources, 140 pp.

MacDonald, L.H., 2000. Evaluating and managing cumulative effects: process and constraints. *Environmental Management* 26(3): 299-315.

MacDonald, L.H., R.W. Sampson, and D.M. Anderson, 2001. Runoff and road erosion at the plot and road segment scale, St. John, U.S. Virgin Islands. *Earth Surface Processes and Landforms* 26: 1-22.

MacDonald, L.H., and J.D. Stednick, 2003. Forests and water: a state-of-the-art review for Colorado. CWRRI Completion Report No. 196, Colorado State University, Fort Collins, Colorado, 65 pp.

MacDonald, L.H., and D.B. Coe, 2007. Influence of headwater streams on downstream reaches in forested areas. *Forest Sciences* 53(2): 148-168.

Madej, M. A., and V. Ozaki, 1998. Channel response to sediment wave propagation and movement, Redwood Creek, California. *Earth Surface Processes and Landforms* 21(10): 911-927.

Martin, Y., and M. Church, 2000. Re-examination of Bagnold's empirical bedload formulae. *Earth Surface Processes and Landforms* 25: 1011-1024.

McGurk, B.J., and D.R. Fong, 1995. Equivalent roaded area as a measure of cumulative effect of logging. *Environmental Management* 19(4): 609-621.

Megahan, W., 1972. An overview of erosion and sedimentation processes on granitic soils. In *Proceedings of the Conference on Decomposed Granitic Soils: Problems and Solutions.* Redding, California.

Megahan, W.F. and G.L. Ketcheson, 1996. Predicting downslope travel of granitic sediments from forest roads in Idaho. *Water Resources Bulletin* 32(2): 371-382.

Merritt, W.S., R.A. Letcher, and A.J. Jakeman, 2003. A review of erosion and sediment transport models. *Environmental Modelling & Software* 18(8-9): 761-799.

Montgomery, D.R., and J.M. Buffington, 1997. Channel-reach morphology in mountain drainage basins. *GSA Bulletin* 109(5): 596-611.

Moody, J.A., and D.A. Martin, 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes and Landforms* 26: 1049-1070.

NCASI, 2003. SEDMODL2 technical documentation and website: http://www.ncasi.org/support/downloads/Detail.aspx?id=5 accessed March 2009.

Neary, D.G., K.C. Ryan, and L.F. Debano, 2005. Wildland fire in ecosystems: effects of fire on soil and water. USDA Forest Service General Technical Report RMRS-GTR-42-vol. 4. Ogden, Utah, 250 pp.

O'Callaghan, J.F., and D.M. Mark, 1984. The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics, and Image Processing* 28: 328-344.

Park, C., 1977. World-wide variations in hydraulic geometry exponents of stream channels: an analysis and some observations. *Journal of Hydrology* 33: 133-146.

Pietraszek, J., 2006. Controls on post-fire erosion at the hillslope scale, Colorado Front Range. M.S. Thesis, Colorado State University, Fort Collins, Colorado, 131 pp.

Reid, L.M., 1993. Research and cumulative effects. USDA Forest Service General Technical Report PSW-GTR-141. Albany, California, 118 pp.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder, 1997. Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). USDA ARS Agriculture Handbook 703, Washington, D.C., 384 pp.

Rice, M.R., R.R. Ziemer, and J. Lewis, 2000. Forest management effects on erosion, sediment, and runoff: lessons from Caspar Creek and northwestern California. *Proceedings of the SAF 2000 National Convention*, Washington D.C. 7 pp.

Riebe, C.S., J.W. Kirchener, D.E. Granger, and R.C. Finkel, 2000. Erosional equilibrium and disequilibrium in the Sierra Nevada, inferred from cosmogenic 26Al and 10Be in alluvial sediment. *Geology* 28(9): 803-807.

Rivenbark, B.L., and C.R. Jackson, 2004. Concentrated flow breakthroughs moving through silvicultural streamside management zones: Southeastern Piedmont, USA. *Journal of the American Water Resources Association* 40(4): 1043-1052.

Robichaud, P.R., R.B. Foltz, and C.H. Luce, 1993. Development of an onsite sediment prediction model for forest roads and timber harvest areas. IAHS Publication 217: 135-140.

Rogers, R.D., 1989. Influence of sparse vegetation cover on erosion and rill patterns: an experimental study. M.S thesis, Colorado State University, Fort Collins, Colorado.

Satterlund, D.R., 1972. Wildland watershed management. The Ronald Press Company, New York, NY. 370 pp.

Stafford, A. and L.H. MacDonald, 2009. Effects of Road Treatments on Sediment Production and Delivery in the Sierra Nevada. AGU Hydrology Days, Colorado State University, Fort Collins, CO.

Stafford, A. and L.H. MacDonald, 2008. Effects of Grading and Waterbars on Road Sediment Production and Delivery. Eos Trans. AGU, 89(53), Fall Meeting Supplemental, Abstract H51D-0857.

Stednick, J.D., 1996. Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology* 176: 79-95.

Sun, G., and S.G. McNulty, 1998. Modeling soil erosion and transport on forest landscape. In *Winning solutions for risky problems: Proceedings of conference of the International Erosion Control Association*. Steamboat Springs, CO, p. 189-198.

Swanson, F.J., and R.L. Fredriksen, 1982. Sediment routing and budgets: implications for judging impacts of forestry practices. In *Sediment Budgets and Routing in Forested Drainage Basins*: 129-137. General Technical Report PNW-141. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Troendle, C.A. and R.M. King, 1985. The effect of timber harvest on the Fool Creek watershed, 30 years later. *Water Resources Research* 21(12): 1915-1922.

Troendle, C.A., and J.M. Nankervis, 2000. Estimating additional water yield from changes in management of national forests in the North Platte Basin. Report submitted to the U.S. Bureau of Reclamation, Lakewood, CO, 51 pp.

Troendle, C. A., and W.K. Olsen, 1994. Potential effects of timber harvest and water management on streamflow dynamics and sediment transport. In *Sustainable Ecological Systems: Implementing an Ecological Approach to Land Management.* Fort Collins, CO, USDA Forest Service, Rocky Mountain Forest and Range Experiment Station**:** p.34-40.

Ursic, S.J., and J.E. Douglass, 1979. The effects of forestry practices on water resources. *Proceedings of the W. Kelly Mosley environmental forum.* Auburn University Press, Auburn, AL. 17 pp.

USDA Forest Service, 1981. Guide for Predicting Sediment Yields from Forested Watersheds. U.S. Dept. Agric., Forest Service, Northern Region, Missoula, Montana, and Intermountain Region, Ogden, Utah. (R1-R4)

USDA Forest Service, 1986. Eldorado National Forest Soil Survey, 358 pp.

VanSickle, J., and R.L. Beschta, 1983. Supply-based models of suspended sediment transport in streams. *Water Resources Research* 19(3): 768-778.

Walling, D.E., 1983. The sediment delivery problem. *Journal of Hydrology* 65: 209-237.

Walling, D.E., 1999. Linking land use, erosion, and sediment yields in river basins. *Hydrobiologia* 410: 223-240.

Waythomas, C.F., and G.P. Williams, 1988. Sediment yield and spurious correlation - toward a better portrayal of the annual suspended sediment load of rivers. *Geomorphology* 1: 309-316.

Water Erosion Prediction Project (WEPP). http://topsoil.nserl.purdue.edu/nserlweb/weppmain/. Accessed 2005-6.

Wells, C.G., R.E. Campbell, L.F. DeBano, C.E. Lewis, R.L. Fredrikson, E.C. Franklin, R.C. Froelich, and P.H. Dunn, 1979. Effects of fire on soil, a state-of knowledge review. USDA Forest Service General Technical Report WO-7. Washington, D.C., 34 p.

Wemple, B.C., J.A. Jones, and G.E. Grant, 1996. Channel network extension by logging roads in two basins, Western Cascades, Oregon. *Water Resources Bulletin* 32(6): 1195-1207.

Westergard, B.E., C.I. Mulvihill, A.G. Ernst, and B.P. Baldigo, 2004. Regionalized equations for bankfull discharge and channel characteristics of streams in New York State: Hydrologic Region 5 in central New York. US Geological Survey, Scientific Investigation Report 2004-5247, 22 pp.

Disturbed WEPP. http://forest.moscowfsl/wsu.edu/fswepp/docs/distweppdoc.html. Accessed 2006.

Whiting, P.J., J.F. Stamm, D.B. Moog, and R.L. Orndorff, 1999. Sediment-transporting flows in headwater streams. *GSA Bulletin* 111(3): 450-466.

Wigmosta, M.S., L. Vail, and D. P. Lettenmaier, 1994: A distributed hydrology-vegetation model for complex terrain, Wat. Resour. Res., 30, 1665-1679.

Wigmosta, M.S., B. Nijssen, P. Storck, and D.P. Lettenmaier, 2002: The Distributed Hydrology Soil Vegetation Model, In Mathematical Models of Small Watershed Hydrology and Applications, V.P. Singh, D.K. Frevert, eds., Water Resource Publications, Littleton, CO., p. 7-42.

Wilcock, P.R., J.C. Schmidt, M.G. Wolman, W.E. Dietrich, D. Dominick, M.W. Doyle, G.E. Grant, R.M. Iverson, D.R. Montgomery, T.C. Pierson, S.P. Schilling, and R.C. Wilson, 2003. When models meet managers: examples from geomorphology. In Wilcock, P.R., and R.M. Iverson (Editors). *Prediction in Geomorphology*. American Geophysical Union, Washington, D.C., 256 pp.

Wilson, C.J., J.W. Carey, P.C. Beeson, M.O. Gard, and L.J. Lane, 2001. A GIS-based hillslope erosion and sediment delivery model and its application in the Cerro Grande burn area. *Hydrological Processes* 15(15): 2995-3010.

Wood, P.J., and P.D. Armitage, 1997. Biological effects of fine sediment on the lotic environment. *Environmental Management* 21(2): 203-217.

Ziegler, A.D., R.A. Sutherland, and T.W. Giambelluca, 2000. Runoff generation and sediment production on unpaved roads, footpaths and agricultural land surfaces in northern Thailand. *Earth Surface Processes and Landforms* 25(5): 519-534.

Table 2.1. Combinations of factors used in the WEPP simulations to create look-up tables for sediment delivery. The factors used to determine the proportions of fine and coarse sediment are marked with an asterisk.

Slope gradient (%)	Land cover type	Soil type	Climate
1*	High severity fire*	Clay loam*	Alturas, CA*
10*	Low severity fire	Sandy loam*	Cheeseman, CO
20*	Short grass*		Forest Glen, CA*
30*	Tall grass		Fenn, ID*
40*	Shrub		Sandpoint, ID
50*	5-year old forest*		Truckee, CA*
	20-year old forest		Wallace, ID

Table 2. 2. Range of predicted to observed bedload transport ratios for 12 formulae as calculated from 410 observations (adapted from Gomez and Church, 1989).

Formula	Range of predicted to observed values
Meyer-Peter	0.13 - 8.6
Schoklitsch (1934)	0.86 - 6.0
Schoklitsch (1943)	0.28 - 6.0
Bagnold	**0.21 - 1.9**
Duboys-Straub	0.73 - 15
Meyer-Peter and Mueller	0.20 - 4.3
Einstein	0.40 - 1421
Parker	0.25 - 5.5
Yalin	0.19 – 20,000
Ackers and White	3.1 - 2500
Ackers and White/Day	1.9 - 368
Ackers and White/Sutherland	2.3 - 1200

Table 2.3. Total road length and total areas disturbed by timber harvest and fire by watershed.

Watershed	Area cut by harvest type (km^2)			Burned area by fire severity (km^2)			Road length
	CASPO thin	Thin	Clearcut	High	Moderate	Low	(km)
Dogtown	0.17	0	2.7	0	0.4	0.05	76
Dry Creek	0.01	2.9	0.7	4.1	0.08	0	47
Steely	0	0	0.9	1.7	0	0.02	33

Table 2.4. Area (km2) and type of timber harvests by year in Dogtown, Dry Creek, and Steely watersheds.

	Dogtown		Dry Creek			Steely
Year	Clearcut	CASPO thin	Clearcut	Thin	CASPO thin	Clearcut
1981	0.08	0.17		0.08		
1984	0.24			0.10		0.14
1985	0.04					0.04
1986	0.52			0.16		0.29
1987	0.32			0.11		0.20
1988	0.07					0.07
1989	2.63		0.74			0.00
1990	0.57					0.01
1992	0.17					
1994	0.23					0.05
1995	0.51			0.51		
1996	0.16			0.16		
1999	0.15			0.14	0.01	
2000	0.04			0.04		
Totals	5.74	0.17	0.74	1.31	0.01	0.80

Table 2.5. Initial percent change in flow and number of years to recovery for different types of timber harvest and different fire severities.

Disturbance type	Initial DQ (%)	Years to recovery
Timber harvest		
Clearcut	25	20
Thin	12	15
CASPO thin	12	15
Fire severity		
High	48	20
Moderate	24	15
Low	12	5

Table 2.6. Initial sediment production rates (SP), years to recovery, and the initial land cover type assigned for undisturbed and disturbed hillslope.

Disturbance	Initial SP ($Mg\ ha^{-1}\ yr^{-1}$)	Years to recovery	Land cover type
Background	0.01	0	20-yr old forest
Timber harvest			
Clearcut	0.224	6	Low severity
Thin	0.112	3	5-yr old forest
CASPO thin	0.112	3	5-yr old forest
Fire severity			
High	12	5	High severity
Moderate	2.4	3	Low severity
Low	1.2	2	Low severity

Table 2.7. Parameter values for the equations used to calculate bankfull discharge (Qb) in cfs, bankfull depth (d) in feet, and bankfull width (w) in feet for each stream arc in the three watersheds. Da is the drainage area (mi2). Qb, d, and w are converted to cms and meters after calculation.

	Parameter	Value
$Q_b = a\ D_a^{\ b}$	a	16.4
	b	0.851
$d = c\ Q_b^{\ f}$	c	0.869
	f	0.221
$w = g\ Q_b^{\ h}$	g	7.7
	h	0.441

Table 2.8. Length of roads, mean arc length, road density, predicted road sediment production, and predicted road sediment delivered to streams by soil type and by watershed.

Watershed	Road length (km)	Mean arc length (m)	Road density (km km^{-2})	Road sediment production (Mg km^{-2} yr^{-1})	Road sediment delivered: sandy loams (Mg km^{-2} yr^{-1})	Road sediment delivered: clay and silt loams (Mg km^{-2} yr^{-1})	Total road sediment delivered (Mg km^{-2} yr^{-1})	Ratio of road sediment production to delivery (%)
Dogtown	76	170	2.9	8.1	0.62	1.8	2.5	30
Dry	47	174	3.6	9.8	1.0	2.9	3.9	39
Steely	33	176	3.7	9.4	0.89	2.5	3.3	36

Table 2.9. Maximum channel length, time needed to attain background sediment yields from model start-up, and the time needed for sediment to reach the outlet based on the distances between the primary disturbances and the watershed outlet. All values are calculated using the MATD procedure.

Watershed	Flow length (km)	Start-up time to background yields (yrs)	Distance to lowest disturbance (km)	Distance to disturbance centroid (km)	Time for sediment to reach outlet after disturbance(yr)
Dogtown	12.2	6	4.7	4.8	3
Dry Creek	9.0	4	3.1	4.7	2
Steely	7.9	3	0.4	2.0	0

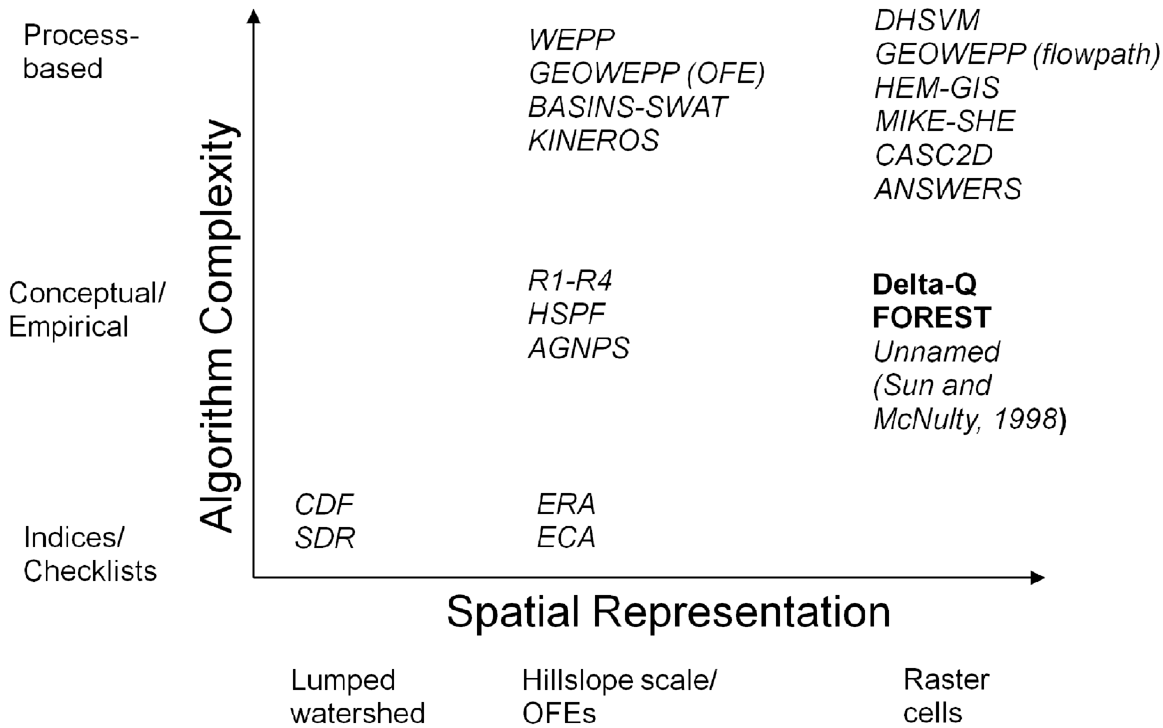


Figure 2.1. Spatial representation and algorithm complexity of selected models for assessing or predicting CWEs in forested watersheds. The two models in bold were developed as part of this research.

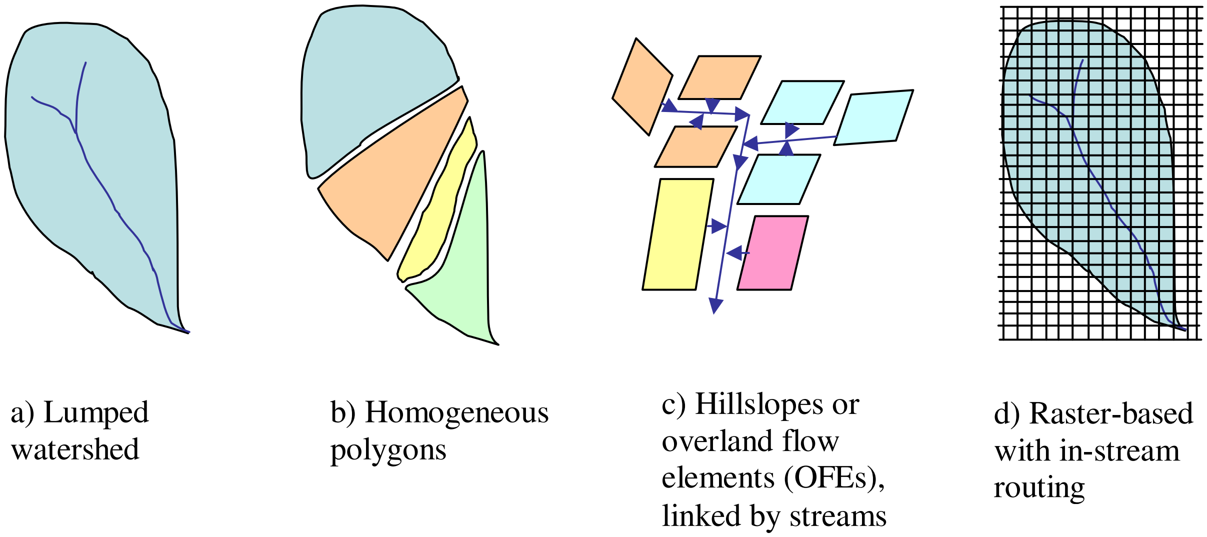


Figure 2.2. Schematic of different spatial representations in CWE models: a) lumped watershed; b) homogeneous polygons; c) OFEs linked by streams; and d) raster-based with hillslope flowpaths (not shown) and in-stream routing.

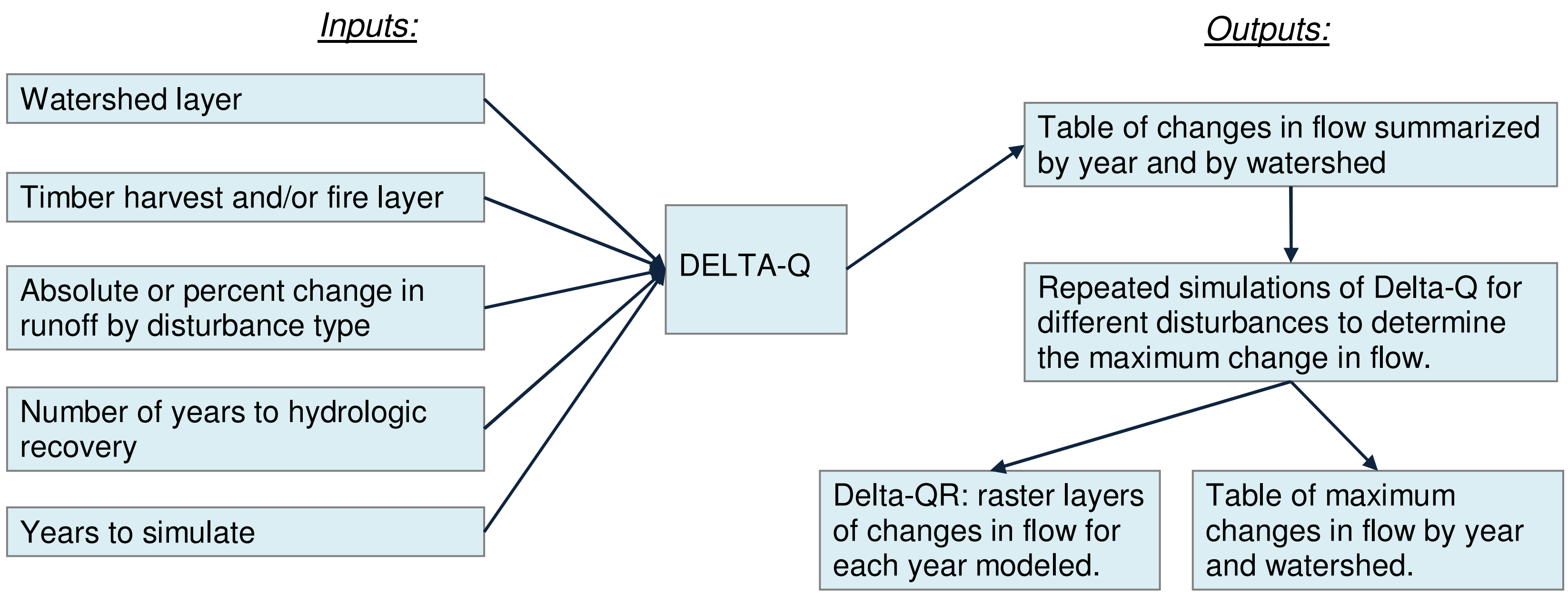


Figure 2.3. Inputs and outputs for Delta-Q.

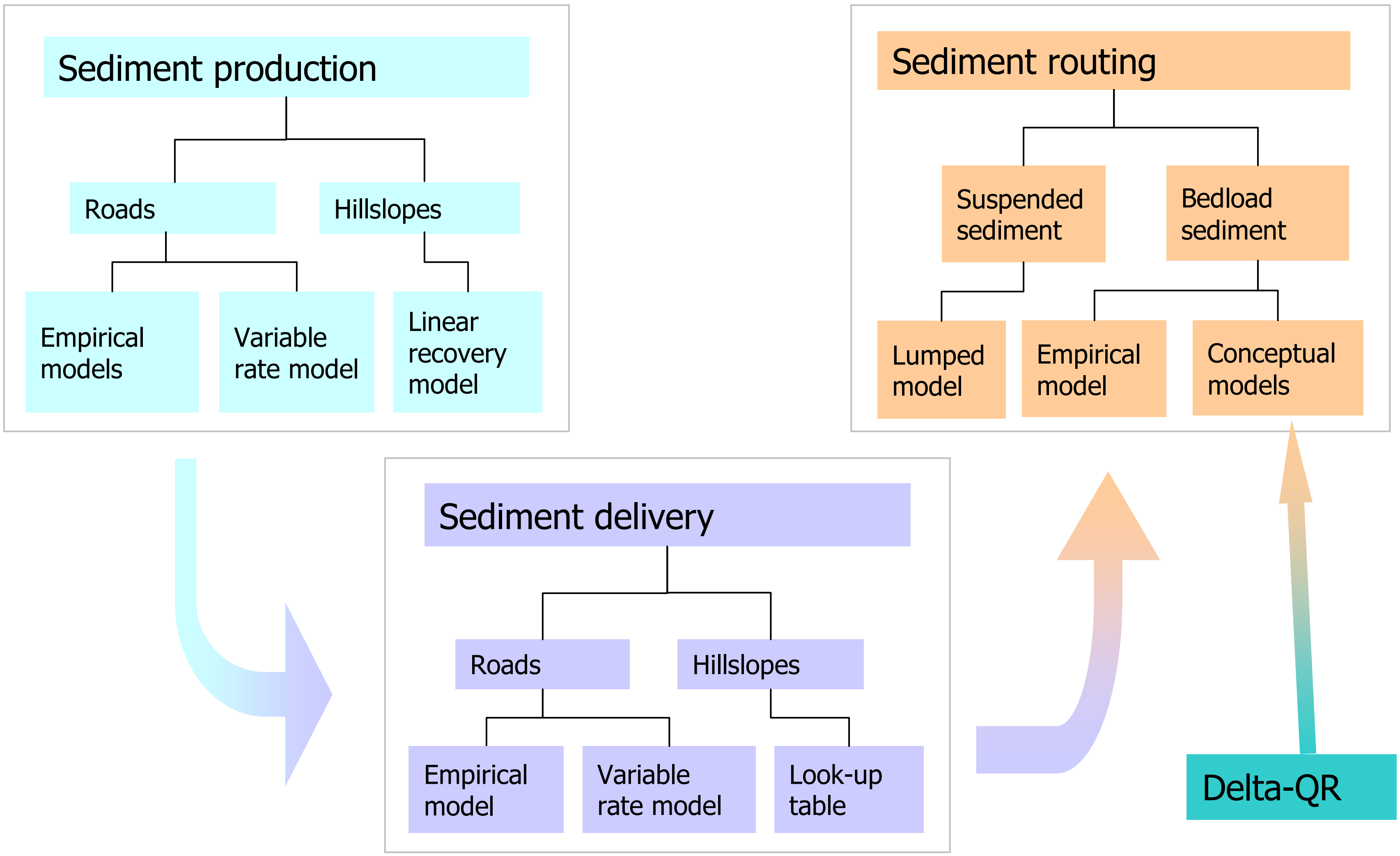


Figure 2.4. Basic structure and flow of FOREST for predicting sediment production, sediment delivery, sediment routing and linkage to Delta-QR.

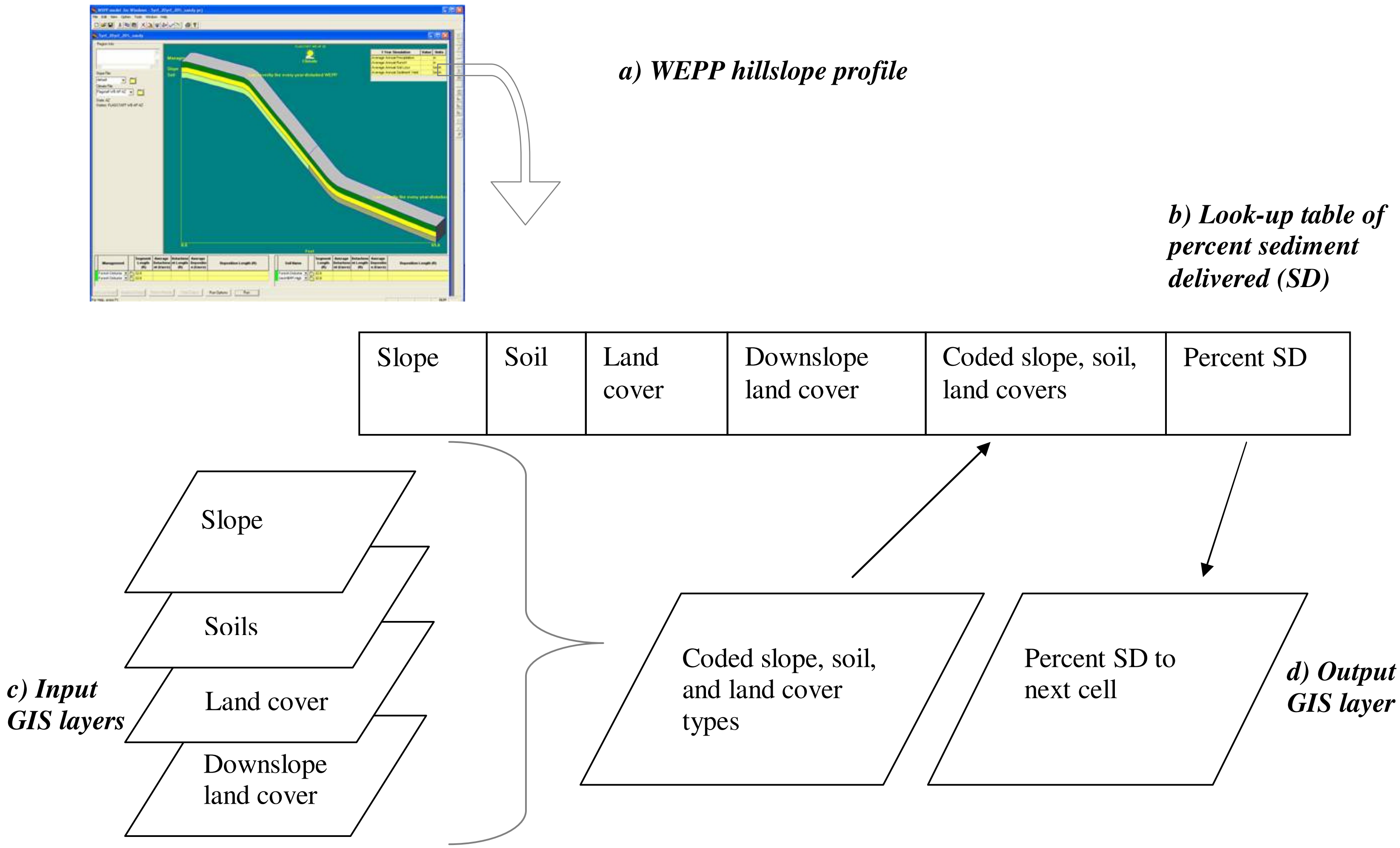


Figure 2.5. Flow chart of the sediment delivery procedure. (a) Data from WEPP hillslope profiles were used to create a lookup table (b). (c) Data from different GIS layers are coded digitwise into one layer. The coded layer is used to look up percent sediment delivered in the table and (d) create a GIS layer of percent sediment delivered for each cell.

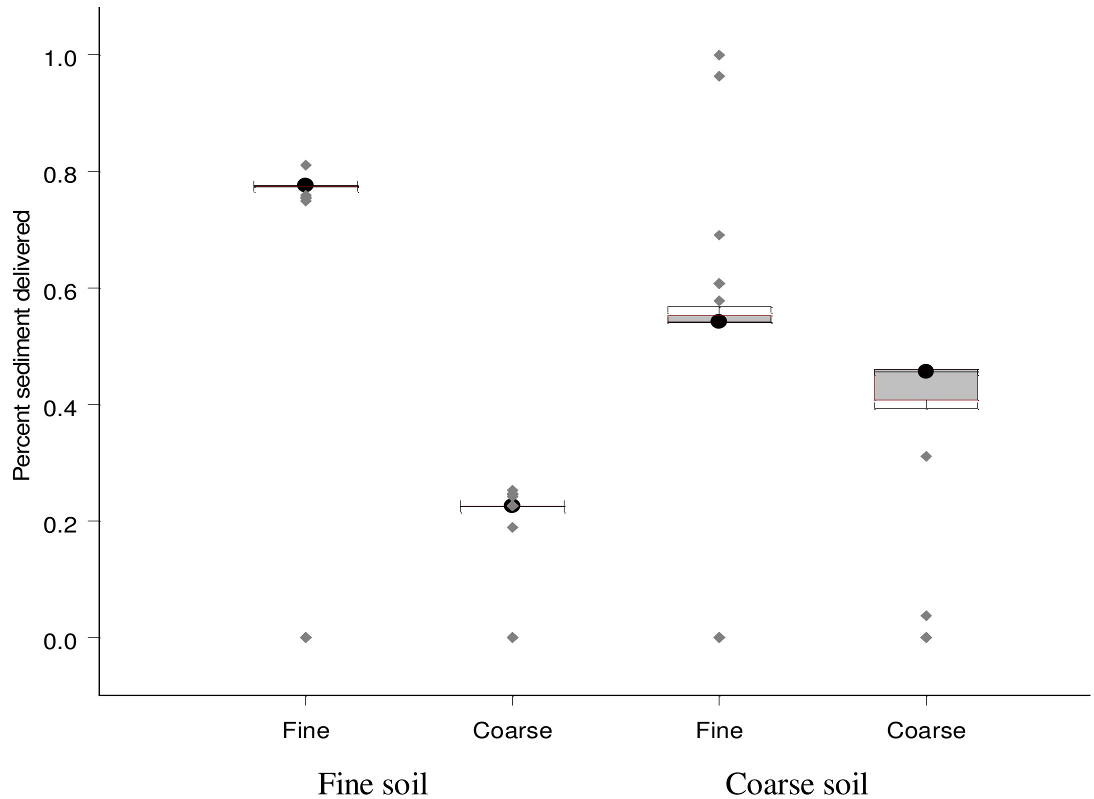


Figure 2. 6. Boxplots of the predicted percent fine (< 0.062 mm) and coarse (0.062 - 2 mm) sediment delivered for a clay loam ("fine") soil and sandy loam ("coarse") soil. The black dots are median values; the boxes represent the 25th and 75th percentiles; the whiskers are ±1.5 times the inter-quartile range; and the grey diamonds are values outside of the whiskers.

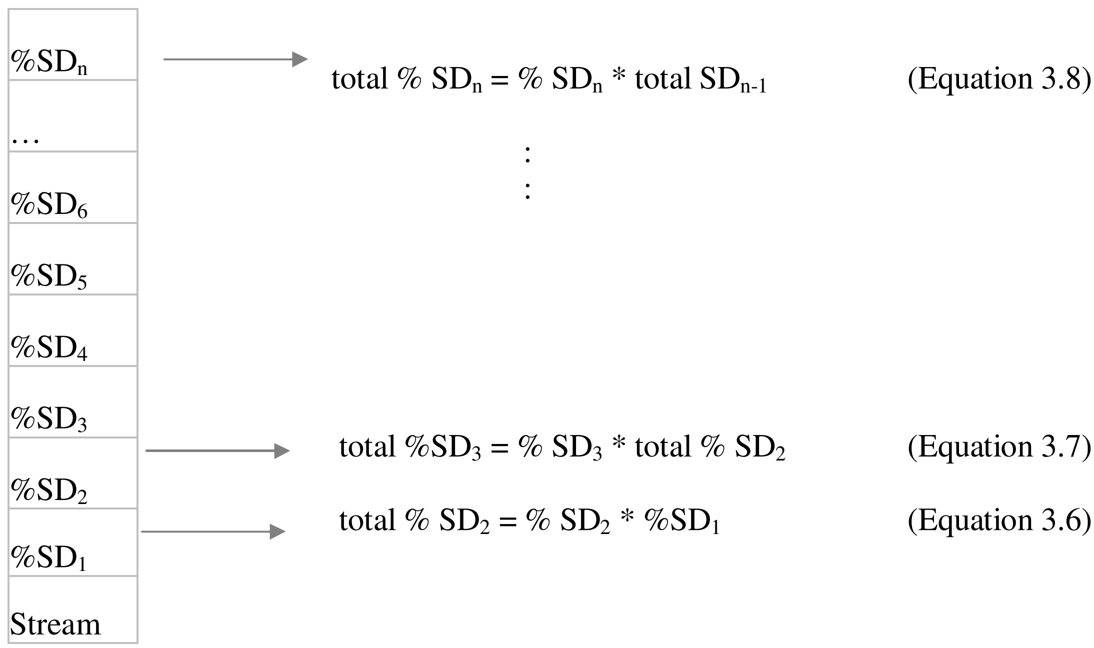


Figure 2.7. Schematic of sediment delivery calculations along a simple hillslope flow path of n cells. The recursive algorithm in FOREST calculates percent sediment delivered for each cell beginning with the lowest cell along each flow path.

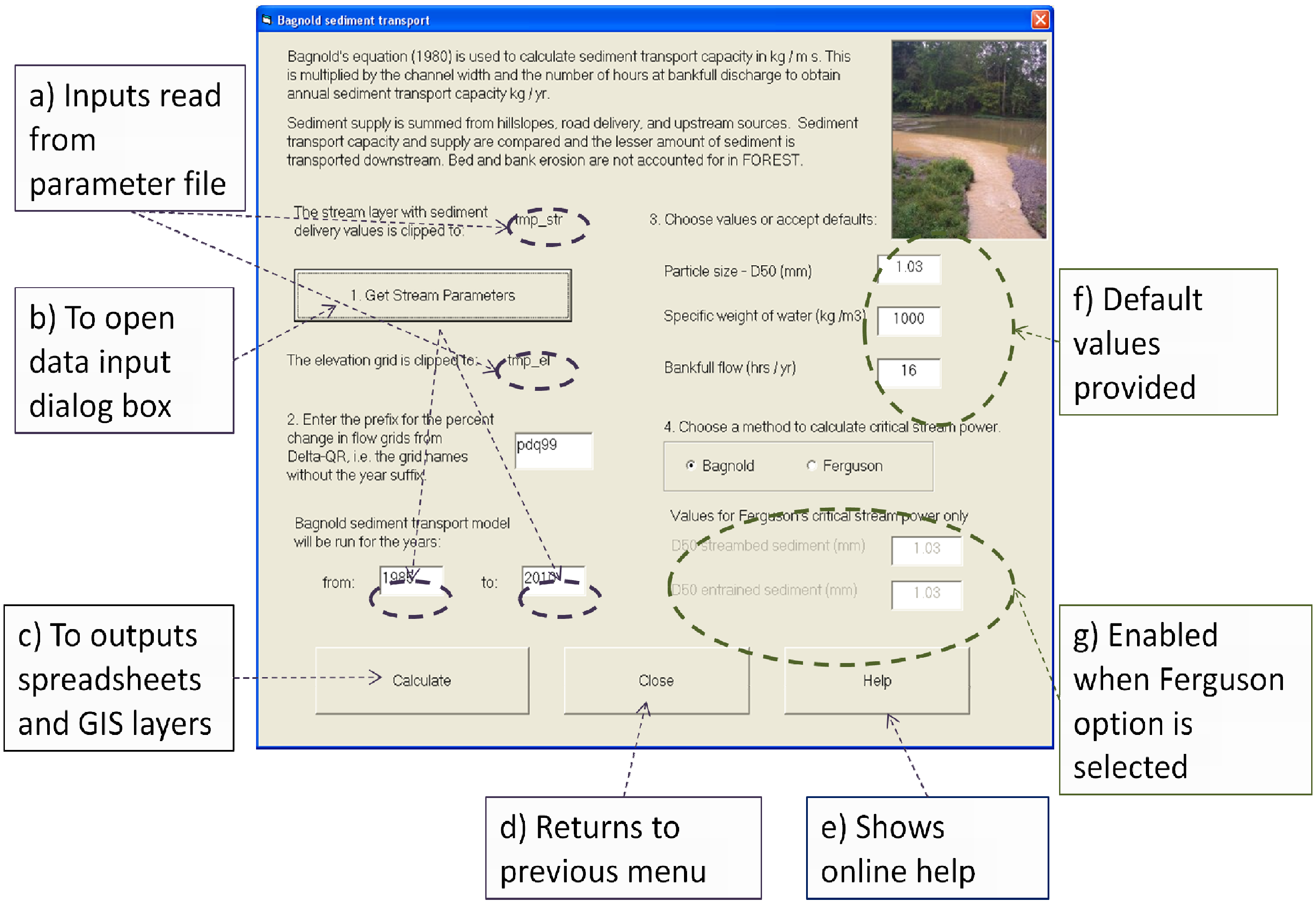
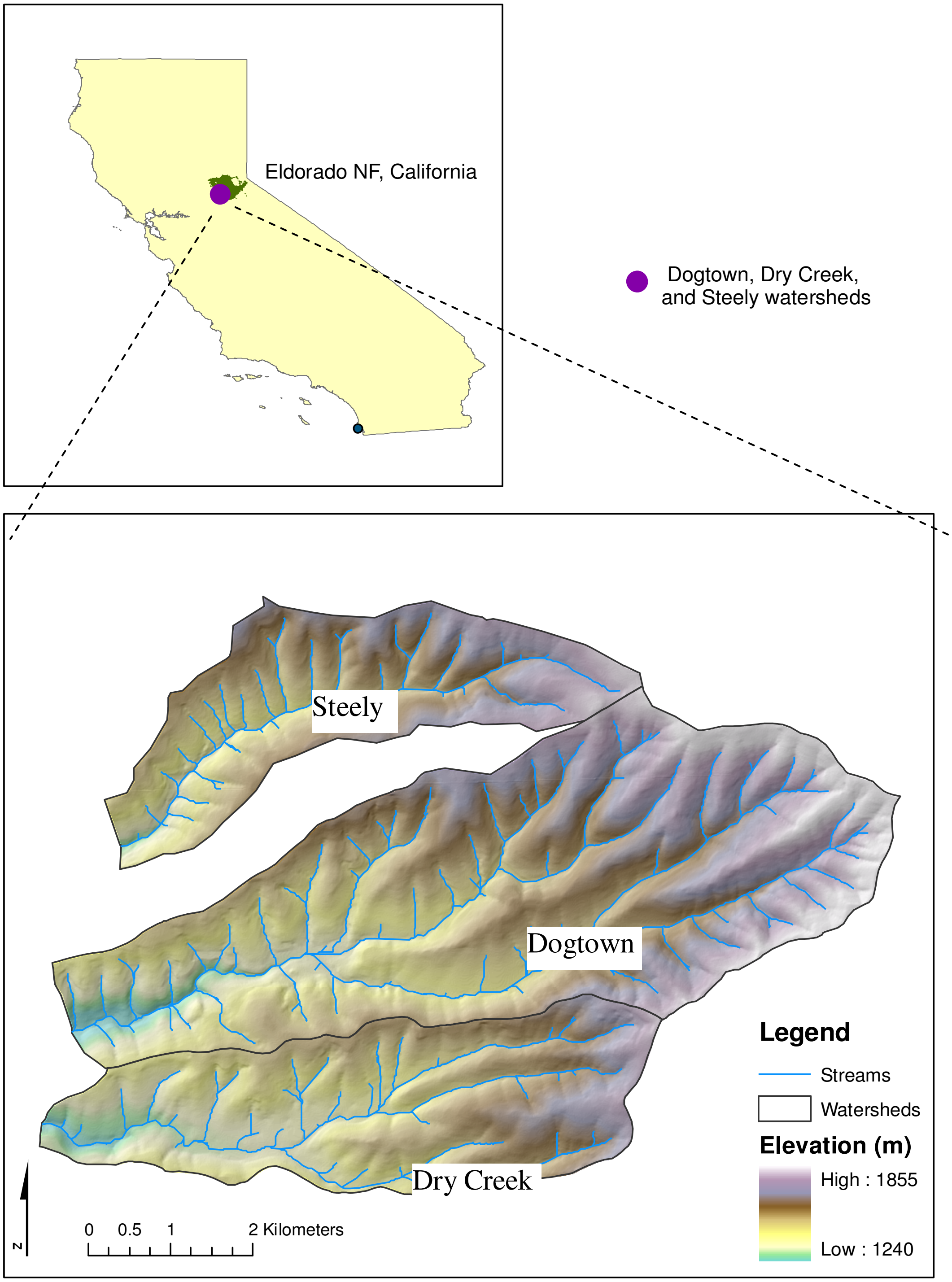
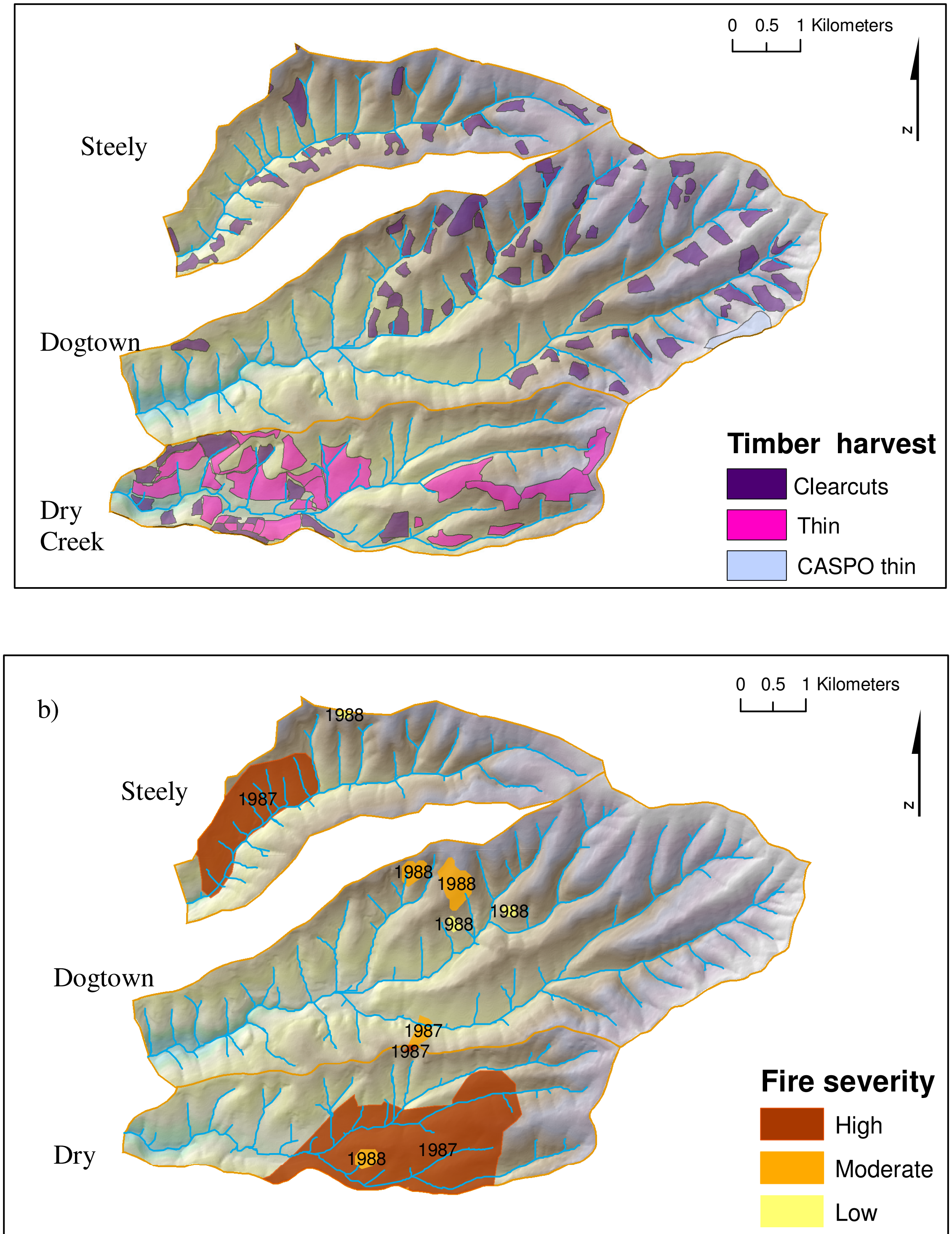


Figure 2.8. An example of the graphical user interface showing step-by-step input instructions, inputs from parameter files, input boxes for parameter values, and command buttons.



Data source: Eldorado NF, 2004; The National Atlas, 2008.

Figure 2.9. Location and topography of Dogtown, Dry Creek, and Steely watersheds in the Eldorado National Forest, California.



Data source: Eldorado NF; The National Atlas. 2008

Figure 2.10.Areas disturbed by: a) different types of timber harvest, and b) fires of varying severities. Years indicate when an area burned.

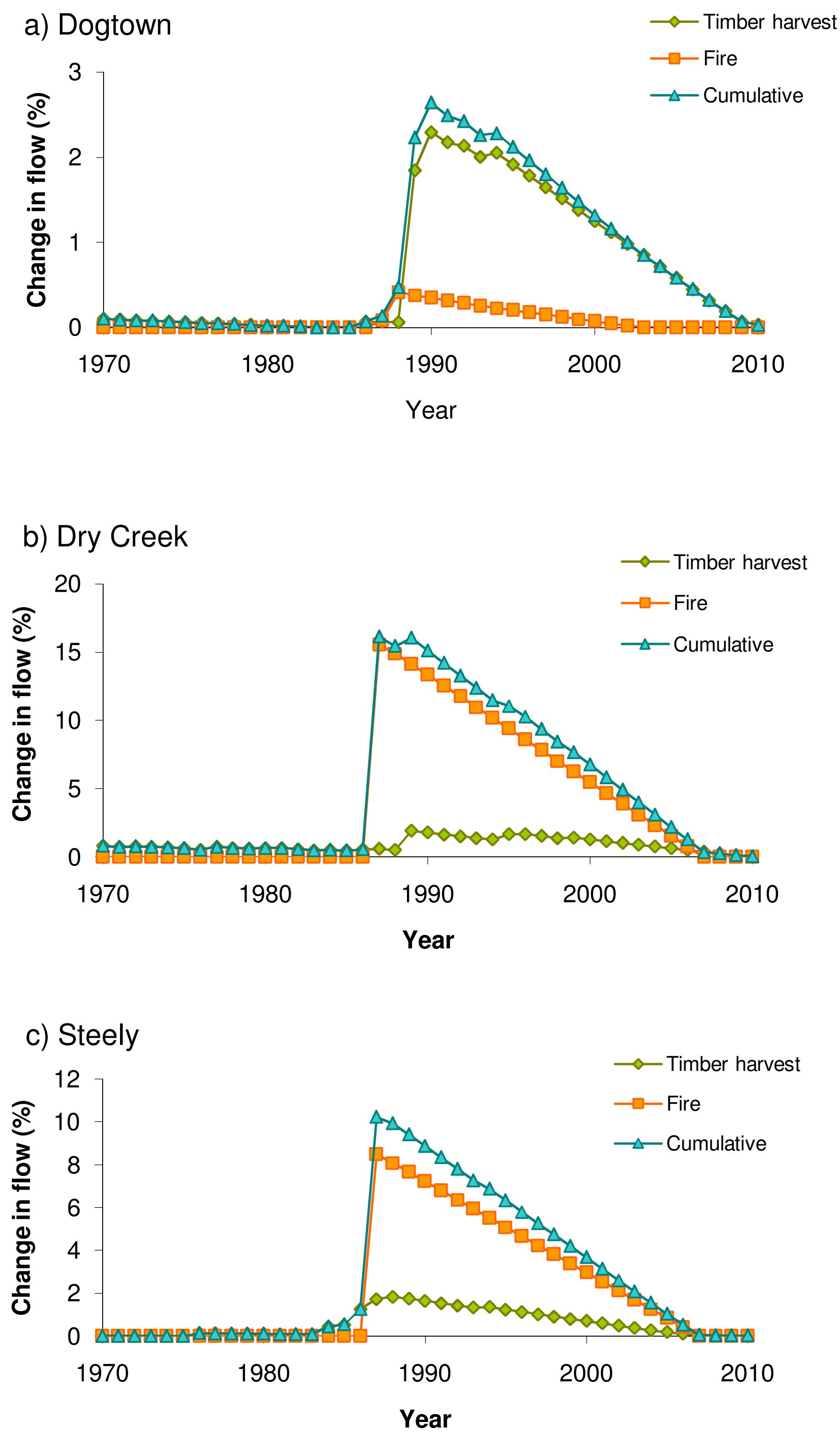


Figure 2.11. Predicted changes in the 99th percentile flows by disturbance type for: a) Dogtown, b) Dry Creek, and c) Steely watersheds from 1970 to 2010.

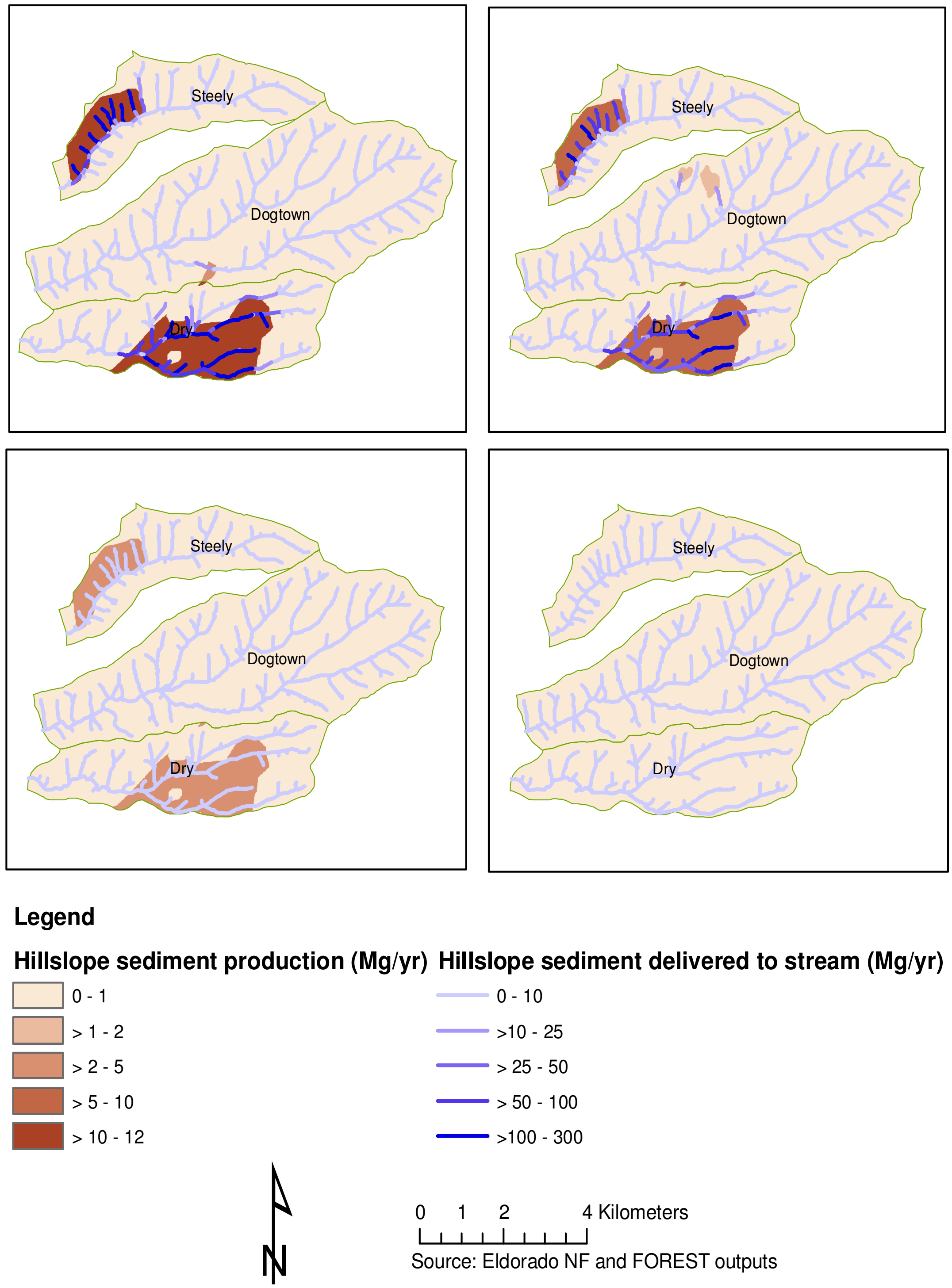


Figure 2.12. Hillslope sediment production and delivery (Mg ha-1 yr-1) to each stream arc in Dogtown, Dry Creek, and Steely watersheds for 1987, 1989, 1991, and 1993.

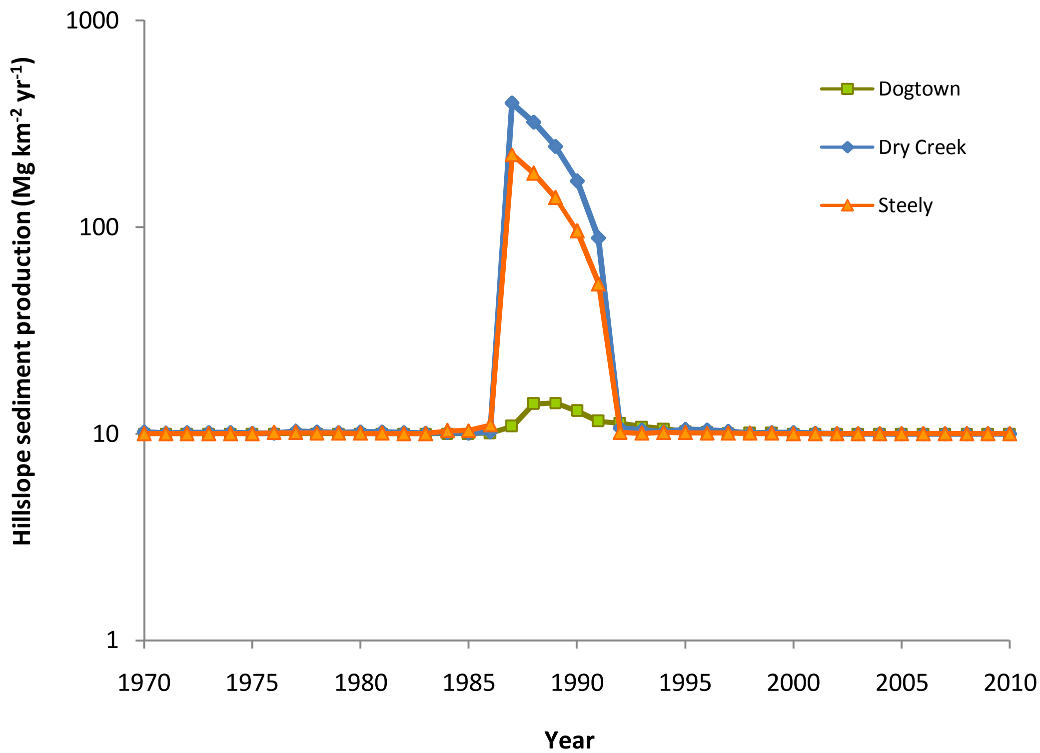


Figure 2. 13. Total hillslope sediment production (Mg km^{-2} yr^{-1}) for Dogtown, Dry Creek, and Steely watersheds from 1970 to 2010.

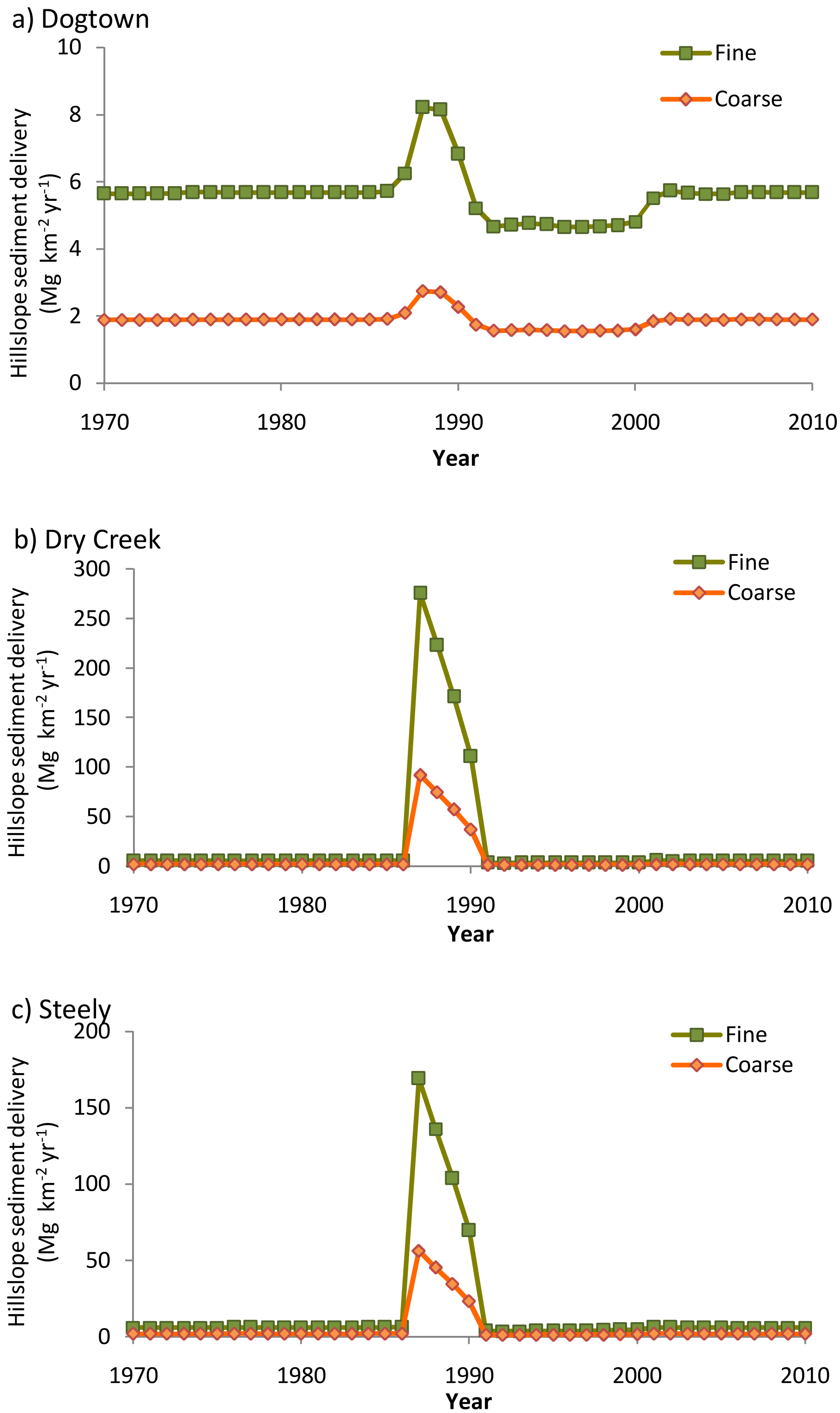
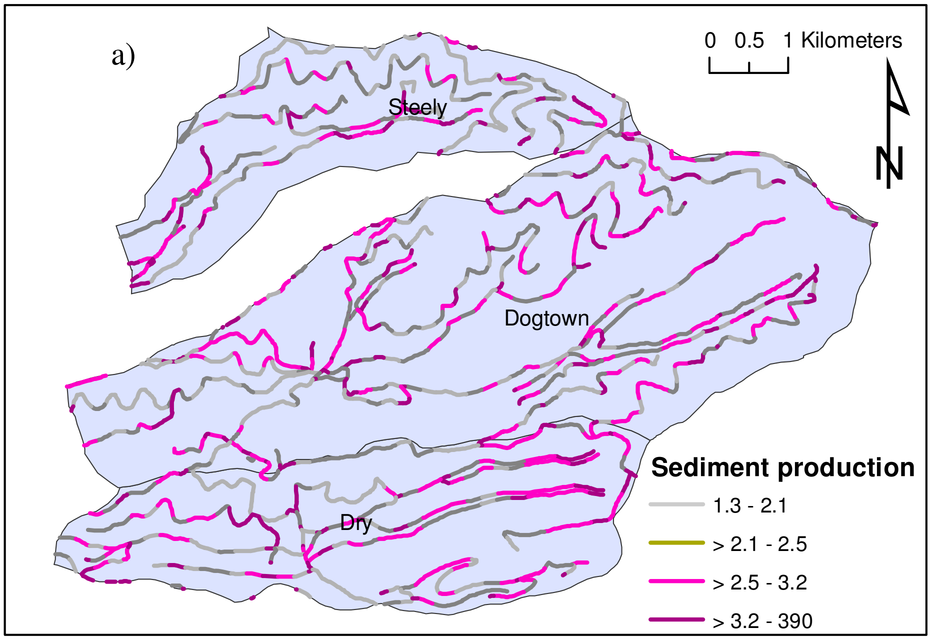


Figure 2.14. Amounts of fine and coarse hillslope sediment delivered to streams normalized by watershed area from 1970 to 2010 for: a) Dogtown; b) Dry Creek; and c) Steely.



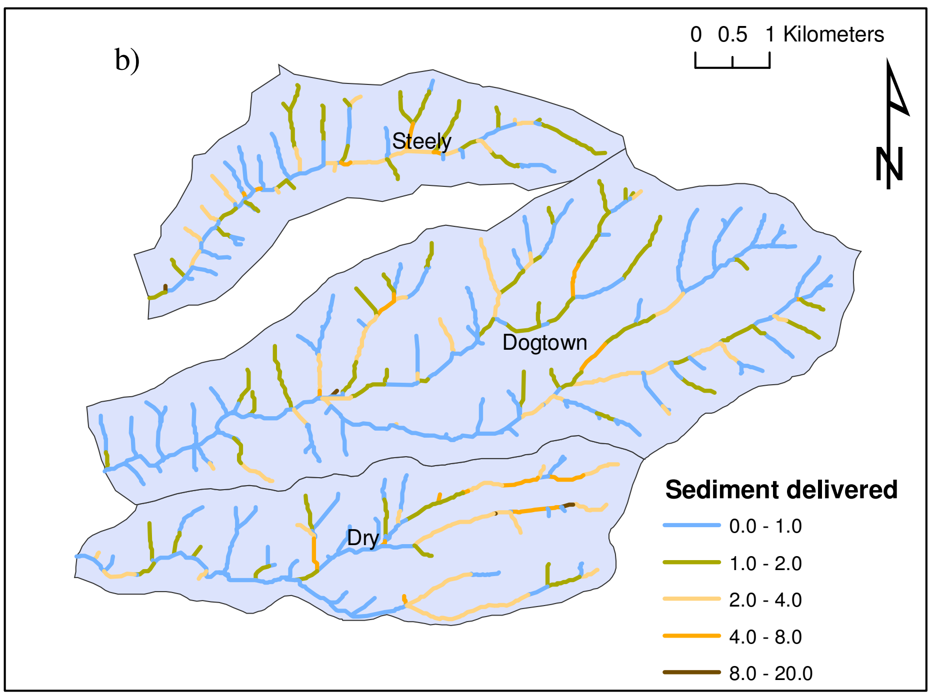


Figure 2.15. a) Annual road sediment production (kg m^{-1} yr^{-1}) and b) road sediment delivered (kg m^{-1} yr^{-1}) to streams for Dogtown, Dry Creek and Steely watersheds.

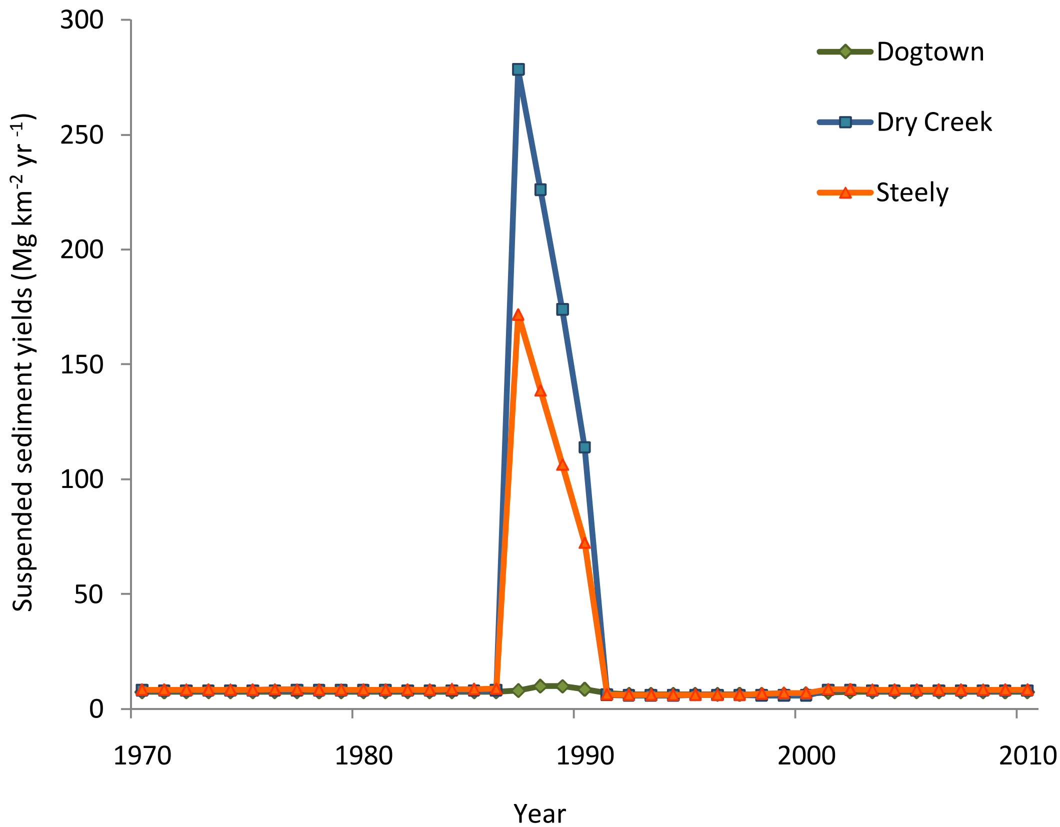
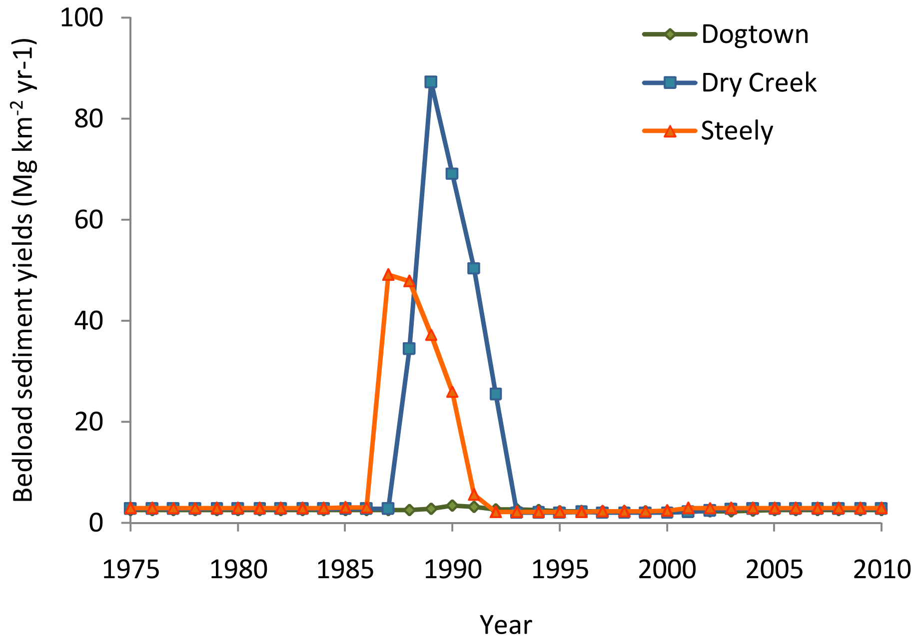


Figure 2.16. Annual suspended sediment yields normalized by watershed area for Dogtown, Dry Creek, and Steely watersheds from 1970 to 2010.

a) MATD



b) Bagnolds equation

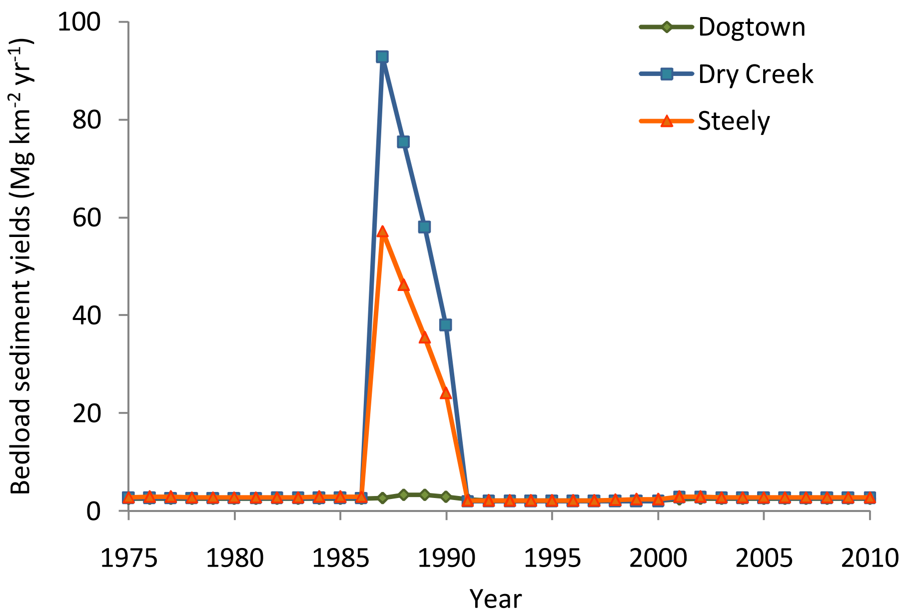


Figure 2.17. Bedload sediment yields normalized by watershed area using: a) MATD and b) Bagnold's equation for Dogtown, Dry Creek, and Steely watersheds from 1970 to 2010.

Chapter 3. Evaluation and sensitivity analyses of Delta-Q and FOREST

3.1 Abstract

Recent land management decisions have been successfully challenged in court because the models used to analyze cumulative watershed effects (CWE) were not sufficiently evaluated with measured data, model assumptions were inadequately disclosed, and descriptions of data did not thoroughly explain the unavailability or inadequacy of data sets The objectives of this study were to: 1) evaluate the hydrologic and sedimentary CWE models, Delta-Q and FOREST, by comparing predicted values to measured data from experimental watersheds at the H.J. Andrews Experimental Forest in western Oregon, Caspar Creek in northwestern California, and Mica Creek in northern Idaho; and 2) conduct a sensitivity analysis of FOREST using data from Caspar Creek.

For Delta-Q the predicted and measured changes in flow were closer for the 50th percentile than the 1st and 99th percentiles because the more extreme flows are more sensitive to the interannual variations in precipitation. Predicted bedload sediment yields in FOREST usually fell within the range of measured values, while the suspended sediment yields were sometimes over-predicted.

Hillslope sediment delivery was most sensitive to the hillslope lengths used in the WEPP model to derive look-up tables of percent sediment delivered values to downslope raster cells. An increase in annual precipitation increased road sediment delivery, but the effect of annual precipitation on hillslope sediment delivery was more complex because of the associated changes in vegetative cover and surface roughness. Reducing the maximum road and stream arc lengths had a smaller effect on sediment yields than the DEM resolution and mean annual precipitation. The sensitivity analyses was also useful for providing guidelines on the range of input values, the types of errors that FOREST can detect, and which errors must be detected by users. The limited amount and variability of data for model evaluation illustrates the need for establishing and maintaining long-term studies on watershed responses to disturbances.

3.2 Introduction

Recent trends in litigation show an increase in challenges to environmental impact statements and environmental assessments concerning proposed timber harvests (Smith, 2005). Agencies such as the USDA Forest Service are required to analyze the cumulative watershed effects (CWE) of past, present and reasonably foreseeable future activities (Reid, 2006). Land management agencies are not required to model CWE since a qualitative approach may be appropriate, but for either approach the agency must take a "hard look" at the issues (Smith, 2005). With recent increases in the availability of GIS, spatial data, and desktop computer technology, computer models have become practical analytical tools. However models must be selected that are suitable for the particular location of the study areas, the available skills and expertise, and to generate outputs at the level of detail approporiate for the analysis (Caminiti, 2004; Eliott *et al.*, 2006).

In order to determine the suitability of a model for a given CWE analysis, the user should examine the model's required inputs and outputs, assumptions and limitations of the internal equations, and previous evaluations of model accuracy using predicted and measured data. A review of litigation identified three main problems with CWE modeling: 1) models were not sufficiently evaluated with measured data; 2) inadequate disclosure of model limitations and assumptions; and 3) inadequate disclosure of incomplete or unavailable data (Reid, 2006). Given these problems, the goals of this study are to: (1) evaluate the CWE models presented in Chapter 2 against measured data; and (2) conduct a sensitivity analysis of the models to help assess model limitations, assumptions, and research needs.

3.2.1 Delta-Q and FOREST

Delta-Q and FOREST are spatially explicit models for calculating the cumulative changes in discharge and sedimentation from road construction, wildfires, and timber harvest activities from small forested watersheds. Delta-Q and FOREST are comprised of 13 conceptual or empirical sub-models that have been taken from previously published studies. The models use readily available GIS data and user-selected parameter values; help files list published data to help guide the user. Default values are also provided. The required GIS data are layers for timber harvest, fire, roads, watersheds, streams, soil texture, and a DEM. The disturbance layers must include the year and type of each disturbance. All calculations are run on an annual time step.

Delta-Q calculates changes in 1^{st}, 50^{th}, and 99^{th} percentile flows due to forest disturbances that result in a loss of canopy cover. The change in flow for each type of disturbance is calculated from the initial change in flow and the assumed linear recovery over a user-specified time period (Chapter 3). Delta-Q produces tables of annual changes in flow for each watershed and raster layers of changes in flow that are used as inputs to the bedload transport sub-models in FOREST.

FOREST calculates sediment production and delivery from hillslopes and roads to streams; the delivered sediment is routed through streams as suspended sediment (particles < 0.062 mm) or as bedload (particles 0.062 to 2 mm). Hillslope sediment production is calculated from a user-specified linear recovery equation similar to that used in Delta-Q. Users can modify erosion by disturbance types as well as an additional, user-selected factor such as soil or geologic type. For undisturbed areas, users can select a background sediment production rate or use the default rate (0.01 Mg ha^{-1} yr^{-1}). Hillslope sediment delivery to the streams is calculated for each raster cell using look-up tables developed with the WEPP model. Different tables have been developed for different climates. The tables list percent sediment delivered values for different slopes, soils, and land cover types and a value is selected for each cell given the characteristics of that cell. Sediment is delivered for pathways that are calculated along each hillslope using a recursive algorithm. Hillslopes that have been subjected to forest harvest and fires recover to mature forest along a gradient of vegetation succession, that is, high severity fire, low severity fire, short grasses, tall grasses, shrub, five year old forest, and lastly, twenty year forest.

Road sediment production is calculated using one of three methods: 1) an empirical formula using road arc gradient and length (Luce and Black, 1999); 2) an empirical formula using road arc gradient, width, graded condition, and storm erosivity (Coe, 2006); or 3) values provided by the user. Road sediment delivery is calculated from an empirical relationship between mean annual precipitation and the proportion of roads connected to streams (Coe, 2006).

The fine sediment delivered to streams is routed in the same year to the watershed outlet as suspended sediment (Waythomas and Williams, 1988; Knighton, 1998). Coarse sediment is routed using either an empirically derived mean annual travel distance (Bunte and MacDonald, 2002) or a parameterization of Bagnold's 1980 equation (Martin and Church, 2000) with the critical stream power calculated by Bagnold's (1980) or Ferguson's method (Ferguson, 2005). Outputs include GIS layers of hillslope and road sediment production and delivery to streams for each year modeled and tables summarizing annual changes in flow and annual sediment yields for each watershed.

3.2.2 Background

3.2.2.1 Model evaluation

Model evaluation tests the ability of a model to accurately reproduce measured values within the designed range of the model (Anderson and Bates, 2001). Model evaluation has often been referred to as model validation; the change from validation to evaluation is not so much a change in procedure as recognition that validation is an incorrect term (Anderson and Bates, 2001; Oreskes and Belitz, 2001). Validation indicates a complete and final test of the model such that accuracy of the model is determined for all cases, sites, and times; validation implies that no other test is necessary. The National Research Council (1990) has stated that "Absolute validity of a model is never determined" since natural systems are open and there is incomplete access to data describing the full historical range of natural phenomena (Oreskes *et al.*, 1994). Hence this paper is more accurately described as an evaluation of Delta-Q and FOREST rather than a validation.

One approach to model evaluation is to compare model predictions against measured data, but this approach has limitations as both measured and modeled data are different representations of reality (Lane and Richards, 2001). Measurements are subject to inaccuracies, such as instrumentation or operator error, and interpolation errors between point samples. Measured data also are frequently scaled up or aggregated in space or time to provide the necessary inputs at the correct spatial or temporal scale for comparison to model predictions (Bloschl and Sivapalan, 1995). Nevertheless, measured values generally are assumed to be the most accurate representation of reality. Thus a model that produces different outputs compared to measured values is assumed to be inaccurate. However a good match between model predictions and measured values does not necessarily signify a completely successful evaluation because there are still untested cases (Beven, 1989; Lane and Richards, 2001).

A second problem with comparing predicted and measured values is that different sets of input values may produce the same output, and this problem is known as equifinality (Oreskes and Belitz, 2001; Beven, 1989). Ideally models should be checked against measured values at each stage of the calculations, but in most cases the intermediate data are not available. For spatially explicit models this is even more difficult, as it is virtually impossible to have measured data for each raster cell or location over the time period being simulated. A similar concern is whether a model produces the correct output for the wrong reasons (Beven, 1989); again an accidentally correct answer does not validate the model.

A different approach to model evaluation uses multiple simulations where input parameters are derived from probability density functions (PDFs) (e.g., Beven, 1989). Outputs are plotted as a frequency distribution and models are tested by their ability to capture the dynamics of physical processes in a realistic manner as evaluated by an expert (Lane and Richards, 2001). The Generalized Linear Uncertainty Estimation (GLUE) method is one example (Beven, 1989). The problem is that this approach is time and data intensive because of the large number of possible permutations (Lane and Richards, 2001). The model interface also would have to allow batch processing since users will not be able to individually run the hundreds or thousands of simulations needed to evaluate the model. Hence the application of this approach is not practical with spatially explicit models.

The use of the word "evaluation" in this paper explicitly recognizes that a complete validation of Delta-Q and FOREST is not possible. Nevertheless, a comparison of predicted outputs to measured values is important for assessing model performance, helping identify model limitations, and identifying specific research needs.

3.2.2.2 Sensitivity analysis

Sensitivity analysis (SA) is the systematic testing of a model's responses to specified changes in inputs, and to the interactions between input parameters (Newham *et al.*, 2003). SA also helps verify that the model calculates accurately as the range of different input data are systematically varied (McCuen, 1973). In spatially explicit models a sensitivity analysis should vary the grain or cell size of the GIS input layers because this can be an important control on the results. A SA of the cell size also is useful to provide guidance on the resolution of the GIS layers needed to run the model and obtain optimal results.

Another important benefit of a sensitivity analysis is that this can help prioritize data collection efforts by defining the relative importance of different parameters (McCuen, 1973). SA also may be part of an iterative process where the model is tested using SA, improvements are implemented as necessary, and the SA is repeated (Newham et al., 2003). Hence SA enables users to better understand model responses, gain an understanding of locations where the model is best applied, and determine the valid range of input parameters (Toy *et al*., 2002).

3.2.3 Objectives

The specific objectives of this study are to 1) compare the predicted watershed-scale outputs from Delta-Q and FOREST to measured runoff from three sets of experimental watersheds and the sediment yields from two experimental watersheds; 2) determine the sensitivity of FOREST to variations in the maximum road and stream arc lengths, digital elevation models (DEMs), and mean annual precipitation inputs; and 3) use the results to identify some of the key assumptions, limitations, and research needs of Delta-Q and FOREST.

3.3 Evaluation sites and data availability

The number of sites for evaluating Delta-Q and FOREST is limited by the availability of measured values. Evaluation of Delta-Q requires daily discharge data to determine the changes in flow duration curves due to treatments; evaluation of FOREST also requires annual suspended and bedload sediment yield data for several years pre- and post-treatment. Suitable data to evaluate Delta-Q were available for paired watersheds at Caspar Creek in northwest California, the H.J. Andrews Experimental Forest in western Oregon, and Mica Creek in north-central Idaho (Figure 3.1; Table 3.1) (Adams *et al.*, 2004; T. Link, Univ. of Idaho, pers. comm., 2006). Since the online help files in FOREST include the some of the changes in flow calculated from the discharge data at Caspar Creek and H.J. Andrews, this study could only use the flow data from the North Fork Watershed in Caspar Creek, the Mack Watershed in H.J. Andrews, and Mica Creek for evaluating Delta-Q.

Longer-term sediment yield data are much more scarce than discharge data. Both the North and South Fork watersheds at Caspar Creek have annual suspended sediment yields and sediment accumulations in weir ponds for 1963 to 2004 (Table 3.1) (Adams *et al*, 2004). The annual measurements of sediment accumulations in the weir ponds were assumed to represent bedload sediment yields, although some smaller particles also may have been trapped. Suspended sediment yields are available at Mica Creek for watersheds 1, 2, and 3. This means that there were two sets of watersheds with suspended sediment data that could be compared to the predicted values, and one set of watersheds with bedload data.

The North Fork (4.73 km^2) and South Fork (4.24 km^2) watersheds at Caspar Creek are dominated by coastal redwoods (*Sequoia sempervirens*) and Douglas fir (*Pseudotsuga menziesii*). The mean annual temperature is 12°C. The area has a rain dominated hydrologic regime and the mean annual precipitation is 1200 mm (Table 3.1). Twelve percent of the North Fork Watershed was clearcut in 1985, 11% in 1989, 15% in 1990, and 11% in 1991 (Figure 3.2). In the South Fork watershed 65% of the timber was selectively harvested from 1971-1973. Given the rapid growth rates, the resprouting ability of the redwoods, and the need to use a different dataset for evaluation, the evaluation of Delta-Q necessarily used the South Fork watershed as the control for the North Fork..

At H.J. Andrews, WS2 (0.57 km^2) was used as the control for the change in flows on the Mack Creek watershed (5.8 km^2) (Table 3.1). From 1957 to 1982, 18% of Mack Creek watershed was clearcut, while WS2 was undisturbed (Figure 3.3). H.J. Andrews has a rain-on-snow regime with a mean annual temperature of 9°C and a mean annual precipitation of 2400 mm (Adams *et al*, 2004).

Mica Creek has a mixed hydrologic regime with a mean annual temperature of 4°C and a mean annual precipitation of 1400 mm (Table 3.1; Karwan *et al,* 2007). Discharge and suspended sediment measurements began in 1991, and the roads were constructed in 1997-98. Fifty percent of watershed 1 was clearcut in 2001, and in late May 2003 the cut area was broadcast burned and replanted (Figure 3.4) (Karwan *et al.*, 2007). Fifty percent of watershed 2 was selectively harvested from 2001 to 2002 (Karwan *et al.*, 2007). Watershed 3 was the undisturbed control for watersheds 1 and 2.

The GIS input data required by Delta-Q and FOREST includes layers of disturbance locations, roads, streams, soil texture, and a DEM. The type and year of occurrence are needed for each disturbance. Delta-Q requires the user to enter an initial change in flow for each type of disturbance and the years to hydrologic recovery. Similarly, FOREST requires an initial sediment production rate for each type of disturbance and the number of years to return to the background sediment production rate. The graphical user interface prompts the user for the necessary parameters based on the user-selected procedures for predicting road erosion, hillslope sediment delivery, and sediment routing, and online help files provide guidance for choosing these parameters..

Most of the data for Caspar Creek and Mica Creek were received from personnel working at these sites. The Mica Creek DEMs were downloaded from the National Map Seamless Server (http://seamless.usgs.gov/, accessed March 2008) and the soils from the NRCS (SSURGO; http://datagateway.nrcs.usda.gov/, accessed March 2008). Data for H.J. Andrews were downloaded from http://www.fsl.orst.edu/lter/ (accessed 2007). The GIS data for each site were processed to UTM North American Datum 1927.

3.4 Methods

3.4.1 Inputs and simulations

The evaluation of Delta-Q and FOREST was made as realistic as possible by selecting input values from the online help files that had been published for areas with similar physical characteristics (Table 3.2). Delta-Q was used to simulate the 1st, 50th, and 99th percent changes in flow for: the North Fork of Caspar Creek from 1990-2004; Mack

Creek watershed at H.J. Andrews from 1980-1995; and watersheds 1 and 2 at Mica Creek for 2001-2005. To remove the effects of climate, the measured changes in flow were adjusted for the interannual variations in total runoff from the control watersheds (Austin, 1999).

The annual suspended sediment yields were calculated using FOREST for the North Fork of Caspar Creek from 1980 to 2005, the South Fork of Caspar Creek from 1965 to 2004, and Watersheds 1, 2, and 3 at Mica Creek from 1992 to 2005. Bedload sediment yields were calculated for the North Fork from 1980 to 2005 and the South Fork from 1965 to 2005. This portion of the evaluation used both bedload routing procedures, the mean annual travel distance and Bagnold's models, in order to evaluate and compare these two procedures (Chapter 2).

The initial hillslope sediment production values and number of years to recovery for Caspar Creek (Table 3.3) and Mica Creek (Table 3.4) were estimated using the online help files in FOREST. A background sediment production rate of 1.35 Mg ha^{-1} yr^{-1} was calculated for undisturbed areas at Caspar Creek (Ferrier *et al*., 2005), while the default background rate of 0.01 Mg ha^{-1} yr^{-1} was used for Mica Creek. Annual road sediment production values were calculated for Caspar Creek using the Luce and Black equation (1999) and default parameter values, and these values did not vary over time. Road sediment production values for Mica Creek were calculated using WEPP: Road batch simulations (http://forest.moscowfsl.wsu.edu/fswepp/, accessed June, 2008; Appendix A). High traffic values were used for the road construction period in 1997-8, while low traffic values were used for all other years.

The climate files for calculating hillslope sediment delivery were developed for each site using Rock:Clime (http://forest.moscowfsl.wsu.edu/fswepp/, accessed June 2008; Appendix B). Road sediment delivery was estimated using the relationship with mean annual precipitation (Coe, 2006). The stream hydraulic geometry values needed to calculate bedload transport at Caspar Creek were taken from Kuck (2000). The default values in FOREST were used for the median sediment particle size (D_{50}), the D_{50} of particles entrenched in the streambed, the D_{50} of particles transported as bedload, and the number of hours per year at bankfull discharge.

3.4.2 Simulation analyses

Predicted and measured output values were compared for changes in flow and sediment yields using the metrics specified below. These metrics were tabulated for changes in flow, suspended sediment yield, and either bedload or total sediment yield. The specific metrics included:

1) means, standard deviations, and coefficients of variation for the predicted and measured data during the time period of the disturbances;

2) the Nash-Sutcliffe coefficient of efficiency, *E*,

$$E = 1.0 - \frac{\sum_{i=1}^{n}(M_i - P_i)^2}{\sum_{i=1}^{n}(M_i - \overline{M})^2} \qquad \text{(Equation 1)}$$

where M is a measured value, *P* is a predicted value, $\overline{M}$ is the mean of the measured values, and *n* is the number of values (Nash and Sutcliffe, 1970). Values of *E* range between minus infinity and one, with values closer to one indicating a better predictive capability. A value of zero indicates that the mean of the measured values is as good as the model, and a negative value indicates that the mean is a better predictor than the model (Nash and Sutcliffe, 1970);

3) Root Mean Squared Error, RMSE,

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} (P_i - M_i)^2 \right]^{0.5} \qquad \text{(Equation 2)}$$

where *M, P*, and *N* are the same as in Equation 1 (Ott and Longnecker, 2001). A lower RMSE indicates a more accurate model (Willmott, 1981).

3.4.3 Sensitivity analyses of FOREST

The sensitivity analyses (SA) of FOREST varied the mean annual precipitation, maximum stream arc length, maximum road arc length, and the DEM cell size. The change in the DEM cell size also necessitated the development of a new set of look-up tables for hillslope sediment delivery, as the baseline tables were developed from WEPP simulations using 20-m long hillslopes (i.e., two 10-m cells). The shift to a 30-m DEM meant that simulations had to be run for 60-m hillslopes (i.e., two 30-m cells). Since the effect of altering the DEM resolution and the look-up tables cannot be reasonably separated, the combination is referred to as DEM_LUT in the rest of this paper.

All of the SAs used data from Caspar Creek because this was the only site with both suspended and weir pond sediment yields. The baseline simulation used the unaltered GIS data and a mean annual precipitation of 1200 mm. Mean annual precipitation was then varied by 25% to evaluate its effect on road and hillslope sediment delivery. The effect of varying mean annual precipitation on hillslope sediment delivery was more complicated than for roads as two new climate files had to be created in Rock: Clime and used to create two new look-up tables for hillslope sediment delivery following the procedure described in chapter 2.

The effects of the changes in mean annual precipitation on hillslope and road sediment delivery were evaluated by calculating a sensitivity index, *S*. S is defined as the ratio of the change in output normalized by the mean output divided by the change in input normalized by the mean input:

$$S = \frac{\left[(O_2 - O_1)/\overline{O_1 O_2}\right]}{\left[(I_2 - I_1 / \overline{I_1 I_2}\right]} \qquad \text{(Equation 3)}$$

where I_1 is the baseline input; O_1 is the baseline output; I_2 is the new input, O_2 is the new output; and $\overline{I_1 I_2}$ and $\overline{O_1 O_2}$ are the averages of the input and output values, respectively (McCuen and Snyder, 1986). By dividing both the outputs and the inputs by the mean values, *S* is independent of the magnitude of the parameters and can be used to compare the effect of varying different parameters (Baffaut *et al.*, 1997).

Field measurements indicate that the length of road and stream segments can affect sediment production, delivery to the stream, and routing though the stream network (Luce and Black, 1999; Bingner *et al.*, 1997). Decreasing the maximum road arc length in the GIS layer may increase road sediment production because road gradients typically increase with decreased road segment length (Luce and Black, 1999) but the magnitude of this effect is much less clear if it is implemented over an entire GIS layer. Similarly, reducing the maximum stream arc length may increase stream gradients and sediment transport capacity. Hence the SA evaluated the effect of reducing the maximum arc lengths for roads and streams to 100 m, 300 m (streams only), 400 m, and 500 m.

3.5 Results

3.5.1 Evaluation of Delta-Q

For each of the treated watersheds there was considerable interannual variability in the measured changes in the 1st, 50th, and 99th flow percentiles (Figures 3.5-3.7). Coefficients of variation ranged up to 24 (Tables 3.5-3.7). The largest percentage differences between the measured and predicted values were generally for the lowest or 1st percentile flows (Figure 3.5), as a small absolute change in flow can result in a large percentage change. Hence the highest RMSE values were for the lowest or 1st percentile flows, and the calculated RMSE for these flows was 667% at Mack Creek, 220% at the North Fork, 63% at watershed 1, and 28% at Watershed 2 (Tables 3.5-3.7). Overall Delta-Q underestimated the measured changes for 1st percentile at Mack Creek and the North Fork, overestimated the measured changes for Watershed 1, and followed the general trend of measured values at Watershed 2 (Figure 3.5). Because Delta-Q only predicts the mean change in flows and does not capture the high interannual variability in low flows (Tables 3.5, 3.6, 4.7), the Nash-Sutcliffe *E* values for the 1st percentile flows ranged from -0.03 at Watershed 2 to -2.32 at Watershed 1 (Tables 3.5-3.7). It is important to recognise that the inability of Delta-Q to account for this interannual variability in low flows will not be a concern when Delta-Q is used to predict future CWE, as the primary concern will be the relative comparison between different management scenarios.

For the 50^{th} percentile flows the predicted values more closely matched the measured values (Figure 3.6). At both Mack Creek and Watershed 2 the predicted changes in flows reflected the general trend of measured changes, while Delta-Q slightly overestimated the observed changes for the North Fork of Caspar Creek and underestimated the observed changes at Watershed 1 (Figure 3.6). RMSE values were typically lower for the 50^{th} percentile flows than the 1^{st} and 99^{th} percentile flows as the RMSE values ranged from 16% for Mack Creek and Watershed 2 to 48% for the North Fork (Tables 3.5-3.7). Nash-Sutcliffe efficiencies ranged from -0.03 for Mack Creek to -6.3 for watershed 2 at Mica Creek, and again the negative values are due in large part to the interannual variations in precipitation that are not being simulated in Delta-Q.

The predicted changes in 99^{th} percentile flows for all watersheds were smaller than the measured changes except Watershed 2 at Mica Creek, where the measured changes in peak flow were negative (Figure 3.7). The coefficients of variation (C.V.) was generally lower for the 99^{th} percentile flows than for 1^{st} percentile flows as the C.V. values ranged from -0.13 at Watershed 2 to 2.15 at the North Fork. The RMSE ranged from 13% at the North Fork to 45% at Watershed 2, and the Nash-Sutcliffe values were again negative (Tables 3.5-3.7) indicating that Delta-Q is better at modelling the 50^{th} percentile flows than either the extreme low or high flows.

3.5.2 Suspended sediment

Suspended sediment yields varied widely between years as well as between sites (Figures 3.8, 3.9) and this variability poses challenges for any CWE model. When normalised by the mean values, the measured values showed much more interannual variability than the predicted values, and this again is because FOREST only predicts mean annual values (Tables 3.8, 3.9). The year-to-year variations in suspended sediment yields are only due to the effect of the different disturbances and recovery over time, while the measured suspended sediment yields vary with precipitation and other factors. These basic differences between what FOREST is able to simulate and what affects the measured values has direct implications for the maximum accuracy that can be expected. Overall, the predicted suspended sediment yields do show the expected cumulative effect from successive disturbances and a sometimes complex recovery over time (Figures 3.8, 3.9).

At the North Fork of Caspar Creek there was a small initial increase in 1985 when 12% of the watershed was clearcut, followed by a linear, 5-year recovery period before the next round of clearcutting increased sediment yields in 1991 (Figure 3.8a). After this second round of harvests there was a relatively sharp decline in sediment yields followed by a slow rise to background levels by 2005.

The drop in predicted sediment yields to below background after each disturbance is due to the predicted decline in hillslope sediment delivery as the vegetation progresses from grasses to shrubs, and then to young forest. Detailed analyses of the look-up tables indicates that Disturbed WEPP predicts lower hillslope sediment delivery percentages from grasses, shrubs, and a young forest than from a mature forest. The lower sediment yields from a disturbed forest are inconsistent with much of the erosion literature (e.g., Beschta, 1978, Croke *et al.,* 1999; Karwan *et al*., 2007), and suggest a problem with the underlying WEPP model. The simplest means for preventing this decline in hillslope sediment delivery would be to set the background sediment delivery rate as the minimum rate for the watershed.

The overall pattern of sediment yields in the South Fork was similar to the North Fork (Figure 3.8b), but the predicted changes in sediment yields were much greater because the initial sediment production rate was assumed to be higher (Table 3.3), timber harvest occurred over a larger proportion of the watershed, and the harvest was more concentrated in time (Figure 3.2). Both the measured and predicted sediment yields were highest immediately after road construction and logging in 1973-74 (Figure 3.8b).

The measured suspended sediment yields were much higher than the predicted values in the years with the highest sediment yields (Figure 3.8). These large differences are due in part to the increase in sediment yields in wet years, but the largest measured sediment yields occurred as a result of several landslides in the 1970's after logging and in 1998 due to the effects of legacy roads and the landslides associated with them (Cafferata *et al.,* 1998). In addition, a splash dam built in the 1880's failed in 1967, and over the next several years this released over 700 m^3 of sediment into the stream channel (Krammes and Burns, 1973). The combination of road construction and the failure of the splash dam produced two to four times as much sediment as expected during the years 1967 to 1975 (Lisle, 1979). Models such as FOREST clearly are unable to simulate the additional sediment due to unpredictable events such as the failure of old splash dams.

FOREST was relatively successful in that the long-term means for measured and predicted suspended sediment yields were relatively similar. For the North Fork the predicted mean suspended sediment yield was 100 Mg km^{-2} yr^{-1}, or 14% larger than the measured value of 88 Mg km^{-2} yr^{-1} (Table 3.8). Mean sediment yields in the South Fork were 36% higher than in the North Fork due to the failure of the splash dam and the landslides mentioned previously, and this explains why the mean predicted sediment yield was 21% lower than the mean measured values (Table 3.8). The pattern of measured and predicted values in Figure 3.8 shows that the predicted sediment yields tended to be too high for the years after timber harvest and the years without disturbances. Reducing the background rate might improve model results.

Suspended sediment yields were generally lower at Mica Creek than at Caspar Creek, and only moderate increases were observed as a result of the timber harvest activities (Table 3.9, Figure 3.9). The relative variability also was much smaller than at Caspar Creek, as the coefficient of variation of suspended sediment yields at Mica Creek was 0.65 compared to 1.6 at Caspar Creek (Tables 3.8 and 3.9). The increases in suspended sediment yields resulting from the construction of the roads were relatively well predicted by FOREST, but the predicted increases resulting from timber harvest were much larger than the observed values for both the clearcut and the thinned watershed (Figure 3.9). In both of these watersheds the peak predicted suspended sediment yield was nearly an order of magnitude higher than the measured value. The predicted and measured values were relatively closely matched in watershed 3, which was only subjected to road building (Table 3.9, Figure 3.9). The predicted increase in suspended sediment yields for this watershed in 1997-1998 was due to road building.

Part of the reason for the large discrepancy between the predicted and measured values in watersheds 1 and 2 is that the timber harvest was followed by the second driest year on record in 2001. Annual precipitation was nearly 30% below the mean value of 1400 mm in 2001, and suspended sediment yields are highly correlated with mean annual precipitation in both Watershed 1 ($r^2 = 0.73$) and Watershed 2 ($r^2 = 0.77$). Figure 3.9 shows that the highest suspended sediment yields occurred in 1996, when the annual precipitation was about 2000 mm (Karwan *et al*., 2007). Hence the tendency for FOREST to overpredict the suspended sediment yields following timber harvest was due to both an assumed input value that was too high and the variability in annual precipitation.

An analysis of the suspended sediment yields during the periods without any disturbances highlights the interannual and spatial variability in suspended sediment yields. In Watershed 3 the predicted sediment yields for the pre-disturbance period of 1991-1996 closely follow the measured values, while in Watersheds 1 and 2 the predicted background rate is slightly overestimated (Figure 3.9). The differences in the measured values between watersheds and years indicate the difficulties of modelling and the need to parameterise individual watersheds as accurately and completely as possible.

3.5.3 Bedload sediment

The pattern of the predicted bedload sediment yields for the North Fork and South Fork of Caspar Creek were similar to the pattern of suspended sediment yields (Figure 3.10). These similarities indicate that all of the coarse sediment delivered to the stream was predicted to rapidly reach the watershed outlet when using Bagnold's equation (Figure 3.10). When the MATD was used, there was a delay in the delivery of the coarse sediment for those disturbances that were further from the outlet than the assumed mean annual travel distance of 2400 m (Figure 3.10). This delay was most evident in the South Fork, where the use of the MATD caused sediment yields to increase in 1971 and 1972, but decrease in 1973, which was the last year of timber harvest (Figure 3.10b). The second and larger peak occurred in 1974 as road sediment and the sediment from the 1973 timber harvest was predicted to reach the watershed outlet (Figure 3.10b). The similar pattern of suspended and bedload sediment yields during the post-harvest recovery period is due to the effect of the assumed sequence of vegetation recovery on coarse and fine hillslope sediment delivery (Chapter 2).

The MATD simulation showed a delay of one year at the start of the modeling period before the simulation attained the background rate in North Fork and South Fork watersheds (Figure 3.10). The delay was due to the length of streams in the watersheds being greater than the mean annual travel distance (Figure 3.10). In larger watersheds several years may be required before the predicted sediment yields will attain the background rate, and users may need to start their simulations several years early in order to eliminate the effect of this lag on background sediment yields.

The MATD method was slightly more accurate than Bagnold's equation as the Nash-Sutcliffe E values ranged from -0.09 to -0.18 for MATD as compared to -0.09 to -0.35 for Bagnold's equation (Table 3.10). E values were negative for both watersheds, but the values in the North Fork were slightly better than in the South Fork (Table 3.10). The lower values for South Fork indicate the difficulty of predicting the large sediment pulses resulting from landslides and the failure of the splash dam.

3.5.4 Sensitivity analysis of raster calculations

Changing the DEM cell size from 10 to 30 m and the associated increase in the length of the hillslopes used to develop the look-up tables (DEM_LUT) sharply decreased the predicted hillslope sediment delivery. With the 10 m DEM_LUT, 80% of the simulations delivered nearly all of the sediment to the next downslope cell. Using a 30 m DEM and 60-m hillslope simulations, 90% of the simulations delivered less than 20% of the sediment to the next downslope cell (Figure 3.11). When the 30 m DEM_LUT was applied to the test watersheds, the predicted background sediment yield decreased by about 98% compared to the background rates for the 10 m DEM_LUT. The decline in peak hillslope sediment yields was greater in the North Fork (97% or 48 Mg km^{-2}) than in the South Fork (89% or 138 Mg km^{-2}) (Figure 3.12). These results are inconsistent with the online help for WEPP which states that soil loss tends to be overestimated for hillslopes that are 50 to 100 m in length. In physical terms, the simulations in FOREST indicate that hillslope sediment delivery is likely to be transport limited for longer hillslopes. Some of the discrepancy between these results and the WEPP documentation may result from the comparison in this study of relative values, whereas the WEPP documentation is referring to absolute values of hillslope sediment delivery.

The watershed-scale sediment yields using MATD also were much lower for the 30 m DEM_LUT simulations than the 10 m DEM_LUT (Figure 3.13). The predicted sediment yields for both the North and South Fork watersheds were much closer to the measured weir pond values when using the 10 m DEM_LUT than the 30 m DEM_LUT. Similar results were obtained when Bagnold's equation was used for routing bedload. These comparisons of hillslope sediment delivery and watershed scale sediment yields indicate that a 10-m DEM should be used for predicting CWE with FOREST.

Increasing the cell size of the DEM from 10 m to 30 m slightly increased road sediment production as the mean road gradient increased from 0.075 m m^{-1} to 0.076 m m^{-1}. This result is contrary to the observations of Luce and Black (2000), and this change in gradient increased the predicted road sediment production by 2% in the North Fork and 4% in the South Fork (Table 3.11). Changing the resolution of the DEM had no effect on road sediment delivery (Table 3.11) as the same roads still fell within the specified buffer zone.

3.5.5 Sensitivity analysis of mean annual precipitation

Changing the mean annual precipitation (MAP) did not have a major effect on sediment delivery from hillslopes and roads. Increasing the MAP by 25% from 1200 mm to 1500 mm increased the predicted peak sediment delivery from hillslopes by 20% in the South Fork and just 2% in the North Fork (Figure 3.14). The greater effect in the South Fork is due to the larger proportion of forest harvest area and a higher sediment production rate following harvest (Krammes and Burns, 1973) (Figure 3.2, Table 3.3). Reducing the MAP from 1200 mm to 900 mm also increased hillslope sediment delivery by 12% in the South Fork and 0.6% in the North Fork. The increase in hillslope sediment delivery with decreasing MAP was attributed to less dense vegetation and the resulting decrease in surface roughness and increase in hillslope sediment delivery (Campbell, 1984; Lane et al., 1995).

Changing the MAP generally had a greater effect on road sediment delivery than hillslope sediment delivery. The greater effect of MAP on road sediment delivery is due to the predicted increase in the width of the sediment delivery zone as MAP increases

(Table 3.11). Increasing the MAP from 1200 mm to 1500 mm increased road sediment delivery by 35% in the North Fork and 7% in the South Fork, while decreasing the MAP from 1200 mm to 900 mm reduced road sediment delivery by nearly 29% in the North Fork and 11% in the South Fork (Table 3.11). The magnitude of the observed changes in road sediment delivery was heavily influenced by the location of the roads relative to the streams. The 70 m buffer for 1500 mm of MAP in the North Fork included 49% more roads than the 60 m buffer, and this explains the 35% increase in predicted road sediment delivery (Table 3.12). In the South Fork watershed the 60 m buffer already included most of the roads that were parallel to the stream, and the 70-m buffer delivery zone only added 7% more roads (Figure 3.2; Table 3.12). Hence the effect of MAP on road sediment delivery will vary according to the location of the streams within a given watershed.

3.5.6 Sensitivity analysis of maximum road arc length

The road sediment production in Caspar Creek very sensitive to maximum road arc length as the equation used to calculate road sediment production uses the road arc length and the road gradient. Reductions in the maximum road arc length greatly increased the predicted sediment production, and the relative effect was much greater in the South Fork than the North Fork (Table 3.11). Limiting the maximum road arc length to 100 m, for example increased the predicted road sediment production by 34% in the North Fork and 137% in the South Fork (Table 3.11). These increases are due to the increases in road gradient as maximum road arc lengths decrease (Figure 3.16).

Road arc length also had a direct effect on the amount of sediment delivered from roads to streams. Limiting the maximum road arc length to 100 m increased road sediment delivery by 20% in the North Fork and 211% in the South Fork relative to the unaltered road arc lengths. Roads within the stream buffer that delivered sediment had a mean gradient of 0.08 m m^{-1} compared to roads in the upslope areas which had a mean gradient of 0.07 m m^{-1}. The increase in road sediment delivery can be attributed to the increase in road sediment production as arc lengths decreased and to the steeper roads that were situated closer to streams.

3.5.7 Sensitivity analysis of maximum stream arc length

Shortening the maximum stream arc length will not affect suspended sediment yields as all of the sediment is assumed to reach the watershed outlet in the same year it is delivered from the hillslope to the stream channel. Shortening stream arc lengths also had very little effect on the predicted sediment yields when bedload transport was estimated using the MATD, as the total predicted yields increased by only 2% in the North Fork and declined by 2% in the South Fork.

Specifying the maximum stream arc length had variable effects on bedload sediment yields using Bagnold's equation. For the North Fork, reducing the maximum stream arc lengths from the unaltered arcs to 300 m resulted in only 1 to 3% decreases in bedload sediment yields (Figure 3.15a).

In the South Fork the changes in maximum stream arc lengths had a more complex effect on bedload sediment yields and this provided important insights into FOREST. Sediment yields dropped by 11% relative to the unaltered streams (Figure

3.15b). This decrease was due to a general decrease in the calculated discharge values as the stream arcs decreased in length. Reducing the maximum stream arc length to 300 m caused the predicted bedload sediment yields to drop to nearly zero for most of the period being modeled (Figure 3.15b). This large decrease was due to one third-order stream arc with a low gradient of 0.0036 m m^{-1} that drains almost 90% of the watershed. The low gradient caused the bedload yield from this arc to be transport limited, while in all but one of the remaining arcs all the coarse sediment was transported further downstream. The tendency for most stream arcs to be supply limited is probably realistic given the assumed mean bedload particle size of 1.03 mm (Knighton, 1998). The only other reach that became supply limited was a first-order stream that drained less than 0.1% of the South Fork.

FOREST was unable to calculate bedload sediment yields in the North Fork watershed using Bagnold's equation when the maximum stream arc length was set to 100 m. The reason was that one stream arc was calculated to have a higher elevation at the downstream end than the upstream end, and the reverse gradient effectively disconnected the stream network. These results indicate that users must be aware of how changing the maximum arc length can affect predicted sediment yields

3.6 Discussion

3.6.1 Evaluation of Delta-Q

The evaluations of Delta-Q highlight the temporal variability in watershed discharge. The four watersheds used to evaluate Delta-Q had coefficients of variation for the selected flow percentiles that ranged up to 2300% (Tables 3.5, 3.6, 3.7). This variability can be attributed to the variations in precipitation, and indicates the difficulty of predicting the changes in low, median, and peak flows after timber harvest. The relative variability is largest for the lowest flows as a small change in the absolute value of a low flow can represent a large percentage change.

Since Delta-Q is designed to predict the average change in flow, it follows that Delta-Q will poorly predict the year-by-year changes in low flows. Comparing the predicted changes in flow over a longer time period also poses problems because forest regrowth can rapidly alter the hydrologic effects of forest harvest. Hence, it can become difficult to separate model error from the error associated with the predicted time to recovery and the predicted shape of the recovery curve. For users who are predicting CWE, modelling the interannual variability of discharge may not be as important as the main objective of Delta-Q which is to predict relative changes in flow due to different forest management scenarios.

Delta-Q assumes a linear hydrologic recovery over time, and this assumption is a reasonable estimate in some cases. At the Fraser Experimental Forest in Colorado, for example, the water yield increase after forest harvest appears to decline linearly (Troendle and King, 1986). In contrast, annual water yields at the Coweeta Experimental Forest in North Carolina recovered more rapidly in the first years after harvest, so an exponential or as a two-step linear model may be more appropriate (Hewlett and Hibbert, 1961). Delta-Q could be modified to include models that specify exponential recovery or two-step linear recovery to calculate changes in flow, but for most forest types, there are insufficient long-term data to specify the shape of the hydrologic recovery to baseline conditions for different flow percentiles.

There also are only limited data on the time period needed for hydrologic recovery of harvested areas. Reported values range from three to sixty years depending on annual precipitation, species, elevation, aspect, type of disturbance, and many other factors (MacDonald and Stednick, 2003). This multitude of controlling factors is why Delta-Q asks users to specify their best estimates rather than assigning values that may not be appropriate.

Delta-Q performed much better for the median or 50th percentile flows, as these are less susceptible to the year-to-year variability in precipitation. If the objective is to compare the magnitude of likely CWEs under different management scenarios or compare current CWEs among watersheds, the interannual variability of discharge is not so important. For these purposes Delta-Q can be a useful tool for predicting the relative changes in flow over time due to the combined effect of timber harvest, roads, and fires.

3.6.2 Evaluation of FOREST

The interannual variability of measured sediment yields is generally much greater than the interannual variability in annual water yields and median flows. The coefficients of variation for measured sediment yields ranged from 58% to 180% (Tables 3.8, 3.9, 3.10). Interannual variability tends to increase as annual sediment yields increase and this may be partly attributed to the greater variability induced by watershed disturbances (Bunte and MacDonald, 1999). In some cases, such as at Mica Creek, the effects of human disturbances on sediment yields are largely subsumed by the variations due to climatic variability. Since FOREST, like Delta-Q, is designed to predict mean annual values, this again means that the traditional *a posteriori* comparison of predicted and measured values is not an accurate means for evaluating FOREST. Despite these limitations, the modeled sediment yields in FOREST were generally within an order of magnitude of measured values.

FOREST is consistent with the first tenet of modeling as it relies on a series of relatively simple models. FOREST is designed to assess the cumulative effect of temporally and spatially varying disturbances over a number of watersheds, including the hydrologic and sedimentary recovery of each disturbance over time. This project has shown that just the process of accounting for these disturbances over space and time adds several degrees of complexity beyond the underlying model equations. FOREST necessarily took a somewhat simplistic approach, and a modular structure was used so that additional complexity could be added as necessary. The four main areas in FOREST that could be improved would be to include mass movements, revise the hillslope sediment delivery sub-model to preclude a decline below the background rate, expand the capability for simulating larger watersheds by adding in-channel sediment production and deposition processes, and allow spatially varying climates within the area being modeled.

At present FOREST only simulates surface erosion, but an increase in mass movements is frequently associated with both timber harvest (e.g., Grant and Wolff, 1991; Montgomery *et al.*, 2000) and roads (e.g., Jones *et al.*, 2001). FOREST could be relatively easily modified to incorporate a GIS layer of historical mass movements, and this would allow past mass movements to be explicitly modeled in terms of the amount and timing of sediment production and delivery. Prediction of future landslides is more difficult, but there are several models that currently predict landslide susceptibility, including SHALSTAB (Dietrich *et al.,* 1993) and SINMAP (Pack *et al.*, 1998). Landslides also can re-occur at the same location (Wieczorek, 1984), and the GIS layer of past mass movements could include probabilities for future landslides at the same locations.

The evaluation results showed that the post-disturbance hillslope sediment delivery can fall below the undisturbed delivery rate during the assumed sequence of vegetative recovery (e.g., Figure 3.8). This result appears to be unrealistic since mature forests generally have the lowest sediment production and delivery rates of any land use due to the high infiltration rate and near complete cover of litter and duff to absorb rainsplash and slow overland flow. The hillslope delivery sub-model in FOREST could be modified by adding a conditional clause that would not allow hillslope sediment delivery to drop below the background rate. While this would be a relatively simply modification, it would further slow the already calculation-intensive process for quantifying hillslope sediment delivery. Any increase in run times will make the model less appealing for users, and this effect should be quantified before a change is implemented.

FOREST was designed to be used on watersheds of up to about 100 km^2 because hillslope processes are often of primary importance. In watersheds larger than about 10 km^2 sediment yields can be increasingly affected by channel processes (Lane *et al.,* 1997). These in-channel processes can include bed and bank erosion, deposition on flood plains and in pools, and particle attrition (Knighton, 1998). The problem is that the flow pathways, sediment storage, and in-channel processes become much more complicated as spatial scale increases, and for this reason FOREST is best used on smaller watersheds. In keeping with the modeling philosophy behind FOREST and the limited data for most applications, FOREST could be modified to include relatively simple empirical or conceptual models to represent some of these in-channel processes. For example, a DEM could be used to estimate channel confinement and channel type, and these can be related to stream channel erosion and deposition (e.g., Rosgen, 1994; Montgomery and Buffington, 1997). The difficulty is to determine which processes need to be included and how much complexity is needed to obtain first-order estimates of potential CWE.

In larger watersheds it may not be appropriate to assume a single, uniform climate, especially if there is a large elevation range (Lane *et al.*, 1997). The sensitivity analysis showed that changing the mean annual precipitation increased sediment production and delivery by up to 35%. FOREST could be modified so that more than one climate-based look-up table could be applied based on a user-defined condition, such as an elevation threshold or a polygon layer. Road sediment delivery also could vary spatially according to an additional GIS layer, such as mean annual precipitation. These changes would further the objective of being spatially explicit.

These four changes to FOREST would make it more realistic, more applicable to watersheds at risk for mass movements, and more appropriate for use in larger watersheds. Some of these changes would be relatively easy to implement, while others would involve the addition of entirely new components. The modular design of FOREST means that such modifications can be added without having to re-program other model components.

3.6.3 Spatial scale, disaggregation, uncertainty, and error

When using spatially explicit models such as Delta-Q and FOREST users, must be aware of how data resolution and scale can affect the results. Delta-Q and FOREST were designed to use commonly available GIS layers, but these vary in their accuracy and resolution. DEMS with 10- or 30-m cells provide seamless coverage for the U.S. and are readily available. The sensitivity analysis showed that the combination of hillslope length in WEPP and cell size in FOREST for the DEM_LUT simulations was an important control on hillslope sediment delivery. The 10-m DEM_LUT simulation provided a much better match to measured sediment yields than the 30-m DEM_LUT simulation. This indicates that any effort to model CWEs with FOREST should use a 10-m DEM with look-up tables derived using the 20 m hillslopes.

Soils data have much lower resolution than DEMs as the soil polygons available from STATSGO have a minimum mapping area of 5 acres or 2 ha. FOREST also requires layers that show the area and type of disturbances, particularly timber harvest and fires. Most large forest landowners and public lands have GIS layers of timber harvest units, but the resolution and accuracy of these layers was not known and could not be easily determined. Similarly, GIS layers are usually available for areas burned by wildland fires, and the accuracy of burn severity maps is an important concern because of the effect of burn severity on runoff and erosion (e.g., Neary 2005; Benavides-Solorio and MacDonald, 2005). The lower resolution of the timber harvest and the soil layers means that these had to be re-sampled to the DEM cell size before they could be used in the hillslope sediment delivery model, but this re-sampling is clearly well beyond the resolution of the original data. The effect of disaggregating the soils and timber harvest data were not been tested in the sensitivity analysis, but the accuracy and resolution of these data will affect the accuracy of the predicted CWE (Thieken *et al.,* 1999).

The sensitivity analysis also identified some unexpected effects resulting from changes in data resolution or scale. First, shortening the length of the maximum stream arc may cause some of the flatter stream arcs to be higher at the downstream end than the upstream end. The disconnection in the stream network meant that FOREST was not able to calculate downstream connectivity and bedload sediment routing for streams with a maximum length of 100 m (Section 4.4.6). FOREST has since been modified such that users can manually edit the stream layer in ArcGIS to ensure downstream connectivity and continue with bedload calculations. Since FOREST saves the GIS layers generated throughout the modeling process, users can investigate any of these layers to determine whether the unexpected results are a result of GIS issues or some other problem.

The second unexpected result occurred when the bedload sediment was 95% lower for 300 m streams compared to all other simulations. Further investigation showed that a stream arc with a very low gradient of 0.0035 m m^{-1} greatly reduced the bedload transport capacity. This effect occurred in the same location as the 100-m arc that had an upwards gradient, but the effect was very different. Hence users must be aware of how data resolution and scale issues can affect the results. As with any model, users need to critically evaluate the results to ensure that they are reasonable and realistic.

3.6.4 Further testing and use of Delta-Q and FOREST

The evaluation of Delta-Q and FOREST conducted here necessarily compared measured and predicted values at the watershed scale. A much more rigorous test would compare the predicted and measured values for individual cells, hillslopes, and or sub-watersheds, as the comparison of spatially lumped values does not provide a complete test of a spatially explicit model for two reasons. First, multiple parameterizations can return the same response ("equifinality") (Beven, 1993). Second, an erroneous parameterization may serendipitously provide the correct output (e.g., Rosso, 1994, in Refsgaard, 2000).). A more comprehensive test of Delta-Q and FOREST would use spatially-explicit runoff and sediment yield data at different spatial scales, but these type of nested data are generally not available.

Delta-Q and FOREST also should be tested against data from locations with different hydrologic regimes and a wide variety of timber harvest and fire treatments. These could include data from a snow-dominated site such as the Fraser Experimental Forest in Colorado, and a more temperate humid site in the eastern US, such as the Parsons or Coweeta Experimental Forests in the central or southern Appalachians.

In addition to evaluating model accuracy, it would be useful for potential users in different parts of the country to run Delta-Q and FOREST to assess their ease of use, cost of use, data requirements, adequacy of the user and technical documentation, data formatting needs, and ease of parameterization (Schroder, 2000). Two beta-testers provided favorable reports on the ease of use early in the model implementation stage. More significantly, the predictions from FOREST sediment production and delivery models were more accurate than predictions using the widely used Soil Water Assessment Tool (SWAT) (N. Hayden, University of California at Santa Barbara, pers.

comm., 2008). These results provide an initial indication that Delta-Q and FOREST do provide a simple, useful, and more accurate tool for assessing cumulative watershed effects in forested areas.

3.7 Conclusions

Delta-Q and FOREST are spatially and temporally explicit models designed to help land managers assess hydrologic and sedimentary CWE due to roads, fires, and forest management. Delta-Q and FOREST were evaluated using data from the H.J. Andrews Experimental Forest in western Oregon, Caspar Creek in northwestern California, and Mica Creek in northern Idaho. A sensitivity analysis of FOREST was conducted using Caspar Creek data.

The evaluation results showed that Delta-Q more accurately predicted the changes in the 50th percentile flows than the 1st or 99th percentile flows. The primary reason is that Delta-Q calculates a mean change in flow, but the 1st and 90th percentile flows are very sensitive to the interannual variations in precipitation. The predicted suspended, bedload, and total sediment yields using FOREST were generally within an order of magnitude of the measured values. Nash-Sutcliffe efficiency values were low, and again this is largely due to the high interannual variability in the measured sediment yields and the fact that the models are designed to predict mean values. At Caspar Creek, the measured sediment yields also were greatly affected by a debris flow and the collapse of an old splash dam; these events contributed to negative E values and indicate the inherent difficulty of predicting CWE.

The sensitivity analysis showed that FOREST was very sensitive to changes in the look-up table and 30 m DEM cell size (DEM_LUT) for the hillslope sediment delivery process which resulted in a decline of up to 98%. Changing the mean annual precipitation from 1200 mm yr^{-1} to 1500 mm yr^{-1} increased hillslope sediment delivery by up to 20% and road sediment delivery by up to 35%. Reducing the maximum length of stream arcs had relatively minor effects unless stream arcs did not follow the DEM. When streams veered away from the lowest flowpath through a DEM, FOREST either found an error in downstream connectivity or for smaller errors, bedload sediment yields were greatly reduced.

The results suggest that Delta-Q and FOREST are a promising "middle ground" approach to assessing and predicting CWE as simpler approaches tend to be subjective and inaccurate. Physically based approaches are limited because of their extensive data needs, level of expertise, and costs to run. Beta users have confirmed their ease of use, and an independent evaluation indicated that FOREST provided more accurate results than the widely-used SWAT model.

Delta-Q and FOREST were designed to predict changes in runoff and sediment yields for different management scenarios in forested watersheds. For this purpose relative values are just as useful as absolute values, and the effect of the interannual variability in precipitation is less important because the amount and timing of future precipitation is not known. The models can be used to compare past and current conditions for different watersheds to help determine where management or restoration activities should be focussed. The spatially-explicit nature of FOREST means that users can assess the sources of sediment on hillslopes and roads using the GIS layers generated by the models. This type of information is essential for helping users to identify relative priorities for hillslope, road, and stream mitigation and restoration activities.

3.8 References

Adams, M.B., L.H. Loughry, and L.L. Plaugher, 2004. Experimental forests and ranges of the USDA Forest Service. General Technical Report GTR-NE-321, USDA Forest Service, Northeast Region, Parsons, WV, 182 pp.

Anderson, M.G. and P.D. Bates, 2001. *Model Validation: Perspectives in Hydrological Science*. J. Wiley, New York, 500 pp.

Austin, S.A., 1999. Streamflow response to forest management: a meta-analysis using published data and flow duration curves. M.S. thesis, Colorado State University, Fort Collins, CO, 265 pp.

Bagnold, R., 1980. An empirical correlation of bedload transport rates in flumes and natural rivers. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, p. 453-473.

Baffaut, C., M.A. Nearing, J.C. Ascough II, and Liu, B.Y., 1997. The WEPP watershed model: II. Sensitivity analysis and discretization on small watersheds. *Transactions of the ASAE* 40(4): 935-943

Baffaut, C., M.A. Nearing and A.D. Nicks, 1995. Impact of CLIGEN parameters on WEPP-predicted average annual soil loss. *Transactions of the ASAE* 39(2):447-457.

Beschta, R.L., 1978. Long-term patterns of sediment production following road construction and logging in the Oregon Coastal Range. *Water Resources Research* 14(6): 1011-1016.

Beven, K.J., 1989. Changing ideas in hydrology—the case of physically-based models. *Journal of Hydrology* 105: 157-172.

Beven, K.J., 1993. Prophecy, reality and uncertainty in distributed hydrological modeling. *Advances in Water Resources* 16: 41-51.

Bingner, R.L., J. Garbrecht, J.G. Arnold, and R. Srinivasan, 1997. Effect of watershed subdivision on simulation runoff and fine sediment yield**.** *Transactions of the ASAE* 40(5): 1329-1335.

Bloschl, G., and M. Sivapalan, 1995. Scale issues in hydrological modelling: a review. *Hydrological Processes* 9: 251-290.

Bravo-Espinosa, M., W.R. Osterkamp, and V.L Lopes, 2003. Bedload transport in alluvial channels. *Journal of Hydraulic Engineering* 129(10): 783-795.

Bunte, K., and L.H. MacDonald, 1999. Scale considerations and the detectability of sedimentary cumulative watershed effects. Technical Bulletin No. 776, National Council for Air and Stream Improvement, Research Triangle Park, NC. 327 pp.

Bunte, K., and L.H. MacDonald, 2002. Predicting the mean annual travel distance of streambed particles: a meta-analysis of published data. *EOS Trans.* Abstract H21G-05, AGU Fall Meet. Suppl., San Francisco, California.

Cafferata, P.H., Spittler, T.E. and Ziemer, R.R., 1998. Logging impacts of the 1970's vs. the 1990's in the Caspar Creek watershed. In *Proceedings of the conference on coastal watersheds: the Caspar Creek Story*. Ziemer, Robert R., technical coordinator. USDA Forest Service GTR-PSW-168, Albany, California, pp. 103-115.

Caminiti, J.E., 2004. Catchment modelling - a resource manager's perspective. *Environmental Modelling & Software* 19(11): 991-6.

Campbell, D.H., 1984. The transport of road derived sediment: a function of slope characteristics and time. M.S thesis, Colorado State University, Fort Collins, Colorado, 46 pp.

Coe, D.B., 2006. Sediment production and delivery from forest management activities in the central Sierra Nevada, CA. M.S. thesis, Colorado State University, Fort Collins, Colorado, 117 pp.

Croke, J., P. Hairsine, and P. Fogarty, 1999. Sediment transport, redistribution and storage on logged forest hillslopes in south-eastern Australia. *Hydrological Processes* 13(17): 2705-2720.

Dietrich, W. E., Wilson, C. J., Montgomery, D. R., McKean, J., Analysis of Erosion Thresholds, Channel Networks and Landscape Morphology Using a Digital Terrain Model, Journal of Geology, v. 101, p. 259-278, 1993.

Disturbed WEPP. http://forest.moscowfsl/wsu.edu/fswepp/docs/distweppdoc.html. Accessed 2006.

Elliot, W.J., K. Hyde, L.H. MacDonald and J. McKean, 2006. Tools for analysis. In W.J. Elliot, and Audin, L.J., eds., *Cumulative Watershed Effects of Fuels Management in the Western United States*. Draft: http://forest.moscowfsl.wsu.edu/engr/cwe/, accessed March, 2006.

Ferguson, R., 2005. Estimating critical stream power for bedload transport calculations in gravel-bed rivers. *Geomorphology* 70(2005): 33-41.

Ferrier, K.L., J.W. Kirchner, and R.C. Finkel, 2005. Erosion rates over millennial and decadal timescales at Caspar Creek and Redwood Creek, Northern California Coast Ranges. *Earth Surface Processes and Landforms* 30(8): 1025-1038.

Grant, G.E., and A.L.Wolff, 1991. Long-term patterns of sediment transport after timber harvest, Western Cascade Mountains, Oregon, USA. In *Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation*. Proceedings of the Vienna Symposium. IAHS Publication No. 203, p. 31-40.

Jones, J. A., F.J. Swanson, B.C. Wemple, and K.U. Snyder, 2001. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. *Conservation Biology* 14(1):76-85.

Karwan, D.L., J.A. Gravelle, and Hubbart, J.A., 2007. Effects of timber harvest on suspended sediment loads in Mica Creek, Idaho. *Forest Science* 53(2): 181-188.

Knighton, D., 1998. *Fluvial forms and processes*. Oxford University Press, New York, NY. 400 pp.

Krammes, J.S., and Burns, D. M., 1973. Road construction on Caspar Creek watersheds - 10-year report on impact. USDA Forest Service Research Paper PSW-93, Berkeley, California, 10 pp.

Kuck, T.D., 2000. Regional HG curves of the South Umpqua area in southwestern Oregon. USDA Forest Service, Rocky Mountain Research Station, Stream Notes, January, p.5-8.

Lane L..J, M.H. Nichols, and G.B. Paige, 1995. Modeling erosion on hillslopes: concepts, theory, and data. Proceedings of the International Congress on Modelling and Simulation (MODSIM ‘95). Binning P, H Bridgeman, B Williams (eds). University of Newcastle, Newcastle, NSW, Australia. Uniprint: Perth, Australia; p. 1-7.

Lane, L.J., M. Hernandez, and M. Nichols, 1997. Processes controlling sediment yield from watersheds as functions of spatial scale. *Environmental Modelling and Software* 12(4): 355-369.

Lane, and K. S. Richards, 2001. The 'validation' of hydrodynamic models: some critical perspectives. In: M.G. Anderson, and P.D. Bates, Eds. *Model Validation: Perspectives on Hydrological Science.* J. Wiley, New York, p.413-438.

Legates, D.R., and G.J. McCabe Jr., 1999. Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research* 35(1): 233-241.

Lisle, T., 1979. The Caspar Creek Watershed. USDA Forest Service Pacific Southwest Research Station, Redwood Sciences Laboratory, Arcata, CA 95521.

Luce, C. H., and T.A. Black, 1999. Sediment production from forest roads in western Oregon. *Water Resources Research* 35 (8) 2561-2570.

Luce, C.H., and T.A. Black, 2000. Erosion over time from forest roads in the Oregon Coast Range. In: C.W. Slaughter, ed., Water Resources Center Report - Centers for Water and Wildland Resources, Report: 98, 140 pp.

MacDonald, L.H., R.W. Sampson, and D.M. Anderson, 2001. Runoff and road erosion at the plot and road segment scale, St. John, U.S. Virgin Islands. *Earth Surface Processes and Landforms* 26: 1-22.

MacDonald, L.H., and J.D. Stednick, 2003. Forests and water: a state-of-the-art review for Colorado, CWRRI Completion Report No. 196, Colorado State University, Fort Collins, Colorado, 65 pp.

Martin, Y., and M. Church, 2000. Re-examination of Bagnold's empirical bedload formulae. *Earth Surface Processes and Landforms* 25: 1011-1024.

McCuen, R.H., 1973. The role of sensitivity analysis in hydrologic modeling. *Journal of Hydrology* 18(1): 37-53.

McCuen, R.H., and W.M. Snyder, 1986. *Hydrologic Modelling: Statistical Methods and Applications.* Prentice Hall, Englewood Cliffs, NJ, 568 pp.

Merritt, W.S., Letcher, R.A., and Jakeman, A.J., 2003. A review of erosion and sediment transport models. *Environmental Modelling & Software* 18(8-9): 761-799.

Montgomery, D.R., and J.M. Buffington, 1997. Channel-reach morphology in mountain drainage basins. *GSA Bulletin* 109(5): 596-611.

Montgomery, D.R., K.M. Schmidt, H.M. Greenberg, and W.E. Dietrich, 2000. Forest clearing and regional landsliding. *Geology* 28(4):311-314.

Nash, J.E., and J.V. Sutcliffe, 1970. River flow forecasting through conceptual models: part 1 - a discussion of principles. *Journal of Hydrology* 10: 282-290.

Neary, D.G., K.C. Ryan, L.F. DeBano, 2005. Wildland fire in ecosystems: effects of fire on soil and water. USDA Forest Service General Technical Report RMRS-GTR-42 vol 4. Ogden, UT, 250 pp.

Newham, L.T.H., Norton, J.P., Prosser, I.P., Croke, B.F.W. and Jakeman, A.J., 2003. Sensitivity analysis for assessing the behaviour of a landscape-based sediment source and transport model. *Environmental Modelling & Software* 18(8-9): 741-751.

Oreskes, N., K. Shrader-Frechette, and K Belitz, 1994. Verification, validation, and confirmation of numerical models in the earth sciences. *Science* 263(5147): 641-646.

Oreskes, N., and Belitz, K., 2001. Philosophical issues in model assessment. In M.G. Anderson, and P.D. Bates, eds. *Model Validation: Perspectives on Hydrological Science*. J. Wiley, New York, p.23-41.

Ott, R.L., and M. Longnecker, 2001. *An introduction to statistical methods and data analysis*. Duxbury, Pacific Grove, California, 1152 pp.

Pack, R. T., D. G. Tarboton and C. N. Goodwin, 1998. *Terrain Stability Mapping with SINMAP, technical description and users guide for version 1.00*. Report Number 4114-0, Terratech Consulting Ltd., Salmon Arm, B.C., Canada.

Refsgaard, J.C., 2000. Towards a formal approach to calibration and validation of models using spatial data. In R. Grayson, and B.G. Bloschl, eds. *Spatial Patterns in Catchment Hydrology: Observations and Modeling*. Cambridge University Press, Cambridge, UK, 404 pp.

Reid, L.M., 2006. Understanding and evaluating cumulative watershed impacts. In: W.J. Elliot, and L.J. Audin, Eds. CWE for fuels management in the Western U.S. http://forest.moscowfsl.wsu.edu/engr/cwe/. Accessed 2006.

Riebe, C.S., J.W. Kirchener, D.E. Granger, and R.C. Finkel, 2000. Erosional equilibrium and disequilibrium in the Sierra Nevada, inferred from cosmogenic 26Al and 10Be in alluvial sediment. *Geology* 28(9): 803-807.

Schroder, A., 2000. WEPP, EUROSEM, E-2D: Results of applications at the plot scale: application of physically based models. In Jurgen Schmidt, ed., *Soil Erosion*. Springer-Verlag, New York, p. 199-250.

Smith, M.D., 2005. Recent trends in cumulative impact case law. Paper presented at the National Association of Environmental Professionals Annual Conference, Alexandria, VA.

Stednick, J.D., 1996. Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology* 176: 79-95.

Swanson, F.J., and R.L. Fredriksen, 1982. Sediment routing and budgets: implications for judging impacts of forestry practices. In *Sediment Budgets and Routing in Forested Drainage Basins*. USDA Forest Service, GTR-PNW-141. Portland, Oregon, p. 129-137.

Thieken, A.H., A.Lucke, B.Diekkruger, and O. Richter, 1999. Scaling input data by GIS for hydrological modeling. *Hydrological Processes* 13: 611-630.

Toy, T.J., G.R. Foster, and K.G. Renard, 2002. *Soil erosion: processes, prediction, measurement, and control*. John Wiley & Sons, New York, 338 pp.

Troendle, C.A. and R.M.King, 1986. The effect of timber harvest on the Fool Creek watershed, 30 years layer. *Water Resources Research* 21(12): 1915-1922.

Troendle, C.A. and R.M.King, 1987. The effect of partial and clearcutting on streamflow at Deadhorse Creek, Colorado. *Journal of Hydrology* 90:145-157.

Water Erosion Prediction Project (WEPP). http://topsoil.nserl.purdue.edu/nserlweb/weppmain/. Accessed 2005-6.

Waythomas, C.F., and G.P. Williams, 1988. Sediment yield and spurious correlation - toward a better portrayal of the annual suspended sediment load of rivers. *Geomorphology* 1: 309-316.

Wieczorek, G., 1984. Preparing a detailed landslide-inventory map for hazard evaluation and reduction. *Environmental and Engineering Geoscience* 21(3):337- 347.

Wemple, B.C., J.A. Jones, and G.E. Grant, 1996. Channel network extension by logging roads in two basins, Western Cascades, Oregon. *Water Resources Bulletin* 32(6): 1195-1207.

Wilmott, C.J., 1981. On the validation of models. *Physical Geography* 2(2): 184-194.

Table 3.1. Location, dominant vegetation, mean annual precipitation, and data used to evaluate and analyze Delta-Q and FOREST from Caspar Creek, H.J. Andrews, and Mica Creek experimental watersheds.

Sites	State	Dominant vegetation	Mean annual precipitation (mm)	Data
Caspar Creek	California	Coastal redwood and Douglas- fir	1200	Discharge (1990 – 2004), suspended sediment (1963-2004), weir pond sediment (1963-2004);
H.J. Andrews	Oregon	Douglas-fir and western hemlock	2400	Discharge (1980 1996)
Mica Creek	Idaho	Western larch, grand fir, western red cedar, Douglas-fir	1400	Discharge (2002 – 2005), suspended sediment (1992-2004)

Table 3.2. Initial changes in flow (DQ) and years to recovery for different types of forest harvest for the 1st, 50th, and 99th flow percentile simulations for Caspar Creek, H.J. Andrews, and Mica Creek.

	1st percentile		50th percentile		99th percentile	
Disturbance	Initial DQ (%)	Years to recovery	Initial DQ (%)	Years to recovery	Initial DQ (%)	Years to recovery
Caspar Creek						
Clearcut	59	20	97	20	-14	20
Select	110	15	36	15	-7.7	15
Tractor harvest	59	20	97	20	-14	20
H.J. Andrews						
Clearcut	350	10	63	10	22	10
Partial cut	640	10	33	10	21	10
Mica Creek						
Clearcut	260	20	27	20	18	20
Thin	14	15	7	15	3.4	15

Table 3.3. Input parameters to FOREST for the North Fork and South Fork of Caspar Creek from 1962 to 2004.

Hillslope sediment production (SP)			**Hillslope sediment delivery**	
Disturbance	Initial SP (Mg ha^{-1} yr^{-1})	Years to recovery	Land Cover	Source
Background rate	1.35	-	-	(Ferrier *et al.*, 2005)
Timber harvest				
Clear cut	2.55	6	Low severity	1.89 * background rate (Lewis, 1998)
Selective cut	12.75	6	Shrub	(Krammes and Burns, 1973)
Tractor harvest	2.55	6	Low severity	1.89 * background rate (Lewis, 1998)
Cell size (m)	10			

Hillslope sediment delivery	
Climate	caspar1200.csv
Max. stream arc length	500 m
Road sediment production	
Equation	Luce and Black, 1999
Max. road arc length	400 m
Road sediment delivery	
Buffer width	60 m
Sediment routing	
Suspended	No parameters
MATD bedload	2400 m
Bagnold bedload	Kuck, 2000

Bedload parameters	Value
$Qb = a A^{b}$	
a	44.8
b	0.918
$d = c Qb^{f}$	
c	0.9
f	0.389
$w = g Qb^{h}$	
g	11.5
h	0.419
D_{50}	1.03 mm
D_i	1.03 mm
D_b	1.03 mm
Q_b duration	16 hrs

Abbreviations

Qb = bank full discharge
A = watershed area
d = depth
w = width
D_{50} = median sediment particle size
D_i= D_{50} of entrenched particles
D_b = D_{50} of bedload particles

Table 3.4. Input parameters to FOREST for Watersheds 1 and 2 at Mica Creek from 1991 to 2005.

Hillslope sediment production (SP)			**Hillslope sediment delivery**	
Disturbance	Initial SP ($Mg\ ha^{-1}\ yr^{-1}$)	Years to recovery	Land Cover	Source
Background rate	0.1	-	-	(Riebe *et al*, 2000)
Timber harvest				
Clear cut	14.0	6	Low severity	Clayton and Kennedy, 1985
Thin	4.4	6	5-yr forest	Clayton and Kennedy, 1985
Cell size (m)	10			

Hillslope sediment delivery	
Climate	mica_id.csv
Max. stream arc length	500 m
Road sediment production	
Equation	WEPP: Road
Max. road arc length	400 m
Road sediment delivery	
Mean annual precipitation	1400 mm
Buffer width	80 m
Sediment routing	
Suspended	No parameters
No bedload	-

Table 3.5. Mean, standard deviation (s.d.), and coefficient of variation (C.V.) of the measured and predicted values for the 1st, 50th, and 99th percentile flows at the North Fork of Caspar Creek from 1990 to 2004, and the Nash-Sutcliffe efficiency (*E*) and RMSE for the comparison of measured and predicted values using Delta-Q.

	1^{st}	50^{th}	99^{th}
Mean (s.d.) of measured percent changes	190 (150)	-10 (37)	4.9 (11)
Mean (s.d.) of predicted percent changes	15 (6.1)	25 (10)	-3.7 (1.5)
C.V. for the measured values	0.8	-3.5	2.2
C.V. for the predicted values	0.4	0.4	-0.4
Nash-Sutcliffe *E*	-1.5	-1.0	-0.9
RMSE (%)	220	48	13

Table 3.6. Mean, standard deviation (s.d.), and coefficient of variation (C.V.) of the measured and predicted values for the 1st, 50th, and 99th percentile flow at Mack Creek, H.J. Andrews from 1980 to 1996, and the Nash-Sutcliffe efficiency(*E*) and RMSE for the comparison of measured and predicted values using Delta-Q.

	1^{st}	50^{th}	99^{th}
Mean (s.d.) of measured percent changes	520 (460)	3.4 (17)	20 (22)
Mean (s.d.) of predicted percent changes	1.2 (0.74)	0.20 (0.12)	0.07 (0.04)
C.V. for the measured values	0.88	5.1	1.1
C.V. for the predicted values	0.61	0.62	0.60
Nash-Sutcliffe *E*	-1.5	-0.03	-0.98
RMSE	670.0	16	29

Table 3.7. Mean, standard deviation (s.d.), and coefficient of variation (C.V.) of the measured and predicted values for the 1st, 50th, and 99th percentile flow at Watersheds 1 and 2, Mica Creek from 2002 to 2005, and the Nash Sutcliffe efficiency (*E*)and RMSE for the comparison of measured and predicted values using Delta-Q.

	Watershed 1			Watershed 2		
	1^{st}	50^{th}	99^{th}	1^{st}	50^{th}	99^{th}
Mean (s.d.) of measured percent changes	51 (40)	30 (8.8)	34 (15)	1.3 (32)	-3.8 (16)	-43 (5.4)
Mean (s.d.) of predicted percent changes	110 (7.8)	11 (0.81)	7.3 (0.54)	7.8 (0.74)	3.0 (0.3)	1.5 (0.15)
C.V. for the measured values	0.78	0.29	0.44	24	-4.2	-0.13
C.V. for the predicted values	0.07	0.07	0.07	0.09	0.10	0.10
Nash-Sutcliffe *E*	-2.3	-6.3	-4.3	-0.026	-0.27	-89
RMSE	63	21	29	28	16	45

Table 3.8. Mean, standard deviation, and coefficient of variation of the measured and predicted annual suspended sediment yields at Caspar Creek from 1963 to 2004, and the Nash-Sutcliffe efficiency (E) and RMSE for the comparison of measured and predicted values.

	North Fork		South Fork	
	Measured	Predicted	Measured	Predicted
Mean (Mg km^{-2} yr^{-1})	88	100	120	95
Standard. deviation	160	21	170	74
Coefficient of variation	1.8	0.21	1.4	0.78
Nash-Sutcliffe E		-0.04		0.04
RMSE (Mg km^{-2})		160		160

Table 3.9. Mean, standard deviation, and coefficient of variation of the measured and predicted annual suspended sediment yields at Mica Creek from 1992 to 2004, and the Nash Sutcliffe efficiency (*E*) and RMSE for the comparison of measured and predicted values.

	Watershed1		Watershed2		Watershed3	
	Measured	Predicted	Measured	Predicted	Measured	Predicted
Mean (Mg km^{-2} yr^{-1})	5.3	120	5.1	10	3.2	2.9
Standard deviation	3.1	180	3.6	4.2	2.1	0.75
Coefficient of variation	0.58	1.5	0.71	0.42	0.67	0.26
Nash-Sutcliffe *E*		-4900		-3.5		0.1
RMSE		210		7.3		1.9

Table 3.10. Mean, standard deviation, and coefficient of variation, of the measured and predicted values for the bedload transport at the North Fork and South Fork of Caspar Creek from 1963 to 2004, and the Nash-Sutcliffe efficiency (*E*) and RMSE for the comparison of measured and predicted values.

	North Fork			
	Measured	MATD	Bagnold	Ferguson
Mean (Mg km^{-2} yr^{-1})	59	34	29	34
Standard deviation	91	7.3	5.9	7.0
Coefficient of variation	1.5	0.21	0.20	0.20
Nash-Sutcliffe *E*		-0.09	-0.13	-0.09
RMSE (Mg km^{-2} yr^{-1})		94	95	95
	South Fork			
	Measured	MATD	Bagnold	Ferguson
Mean (Mg km^{-2} yr^{-1})	49	35	35	35
Standard deviation	47	24	27	27
Coefficient of variation	0.95	0.69	0.77	0.77
Nash-Sutcliffe *E*		-0.18	-0.35	-0.35
RMSE (Mg km^{-2} yr^{-1})		50	53	53

Table 3.11. The differences in annual road sediment production and delivery due to varying the DEM resolution from 10 to 30 m, mean annual precipitation from 900 to 1500 mm, maximum road arc length from100 to 500 m, stream arc lengths from 100 to 500 m, and using unaltered arc lengths for the North Fork and South Fork watersheds at Caspar Creek.

North Fork

DEM (m)	Mean annual precipitation (mm)	Max arc length for roads (m)	Max arc length for streams (m)	Produced (Mg yr $^{-1}$)	Delivered (Mg yr $^{-1}$)	Delivered/ Produced
10	1200	500	400	97	17	0.18
30	1200	500	400	99	17	0.17
10	900	500	400	97	12	0.12
10	1200	500	400	97	17	0.18
10	1500	500	400	97	23	0.23
10	1200	100	400	125	20	0.16
10	1200	400	400	99	17	0.17
10	1200	500	400	97	17	0.18
10	1200	Unaltered	Unaltered	93	17	0.18

South Fork

DEM (m)	Mean annual precipitation (mm)	Max arc length for roads (m)	Max arc length for streams (m)	Produced (Mg yr $^{-1}$)	Delivered (Mg yr $^{-1}$)	Delivered/ Produced
10	1200	500	400	57	21	0.37
30	1200	500	400	59	28	0.47
10	900	500	400	57	25	0.43
10	1200	500	400	57	28	0.49
10	1500	500	400	57	30	0.52
10	1200	100	400	97	56	0.57
10	1200	400	400	61	29	0.47
10	1200	500	400	57	28	0.49
10	1200	Unaltered	Unaltered	41	18	0.43

Table 3.12. The differences in the sensitivity index (S) for peak and total hillslope sediment delivered, and road sediment delivered when mean annual precipitation is changed from 900 mm to 1500 mm. The baseline simulation used a mean annual precipitation of 1200 mm.

	North Fork		South Fork	
Mean annual precipitation	900 mm	1500 mm	900 mm	1500 mm
Peak hillslope sediment delivery	-0.02	0.09	-0.40	0.84
Total increased hillslope sediment delivery after treatments	-0.03	0.08	-0.25	0.53
Roads sediment delivery	1.29	1.21	0.45	0.27
Stream buffer width (m)	50	70	50	70
Percent change in road length with change in mean annual precipitation	37%	49%	12%	7%

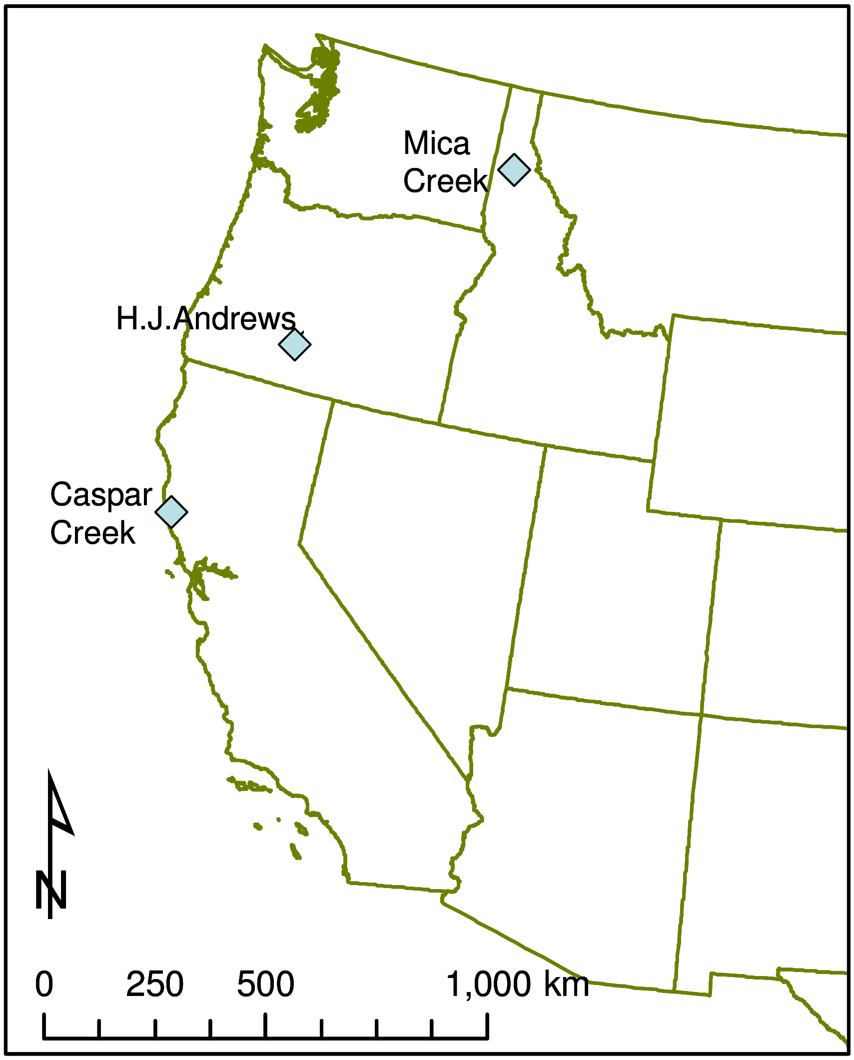


Figure 3.1. Locations of the Caspar Creek, H.J. Andrews, and Mica Creek experimental watersheds used to evaluate Delta-Q and FOREST. The data from Caspar Creek also were used for the sensitivity analyses.

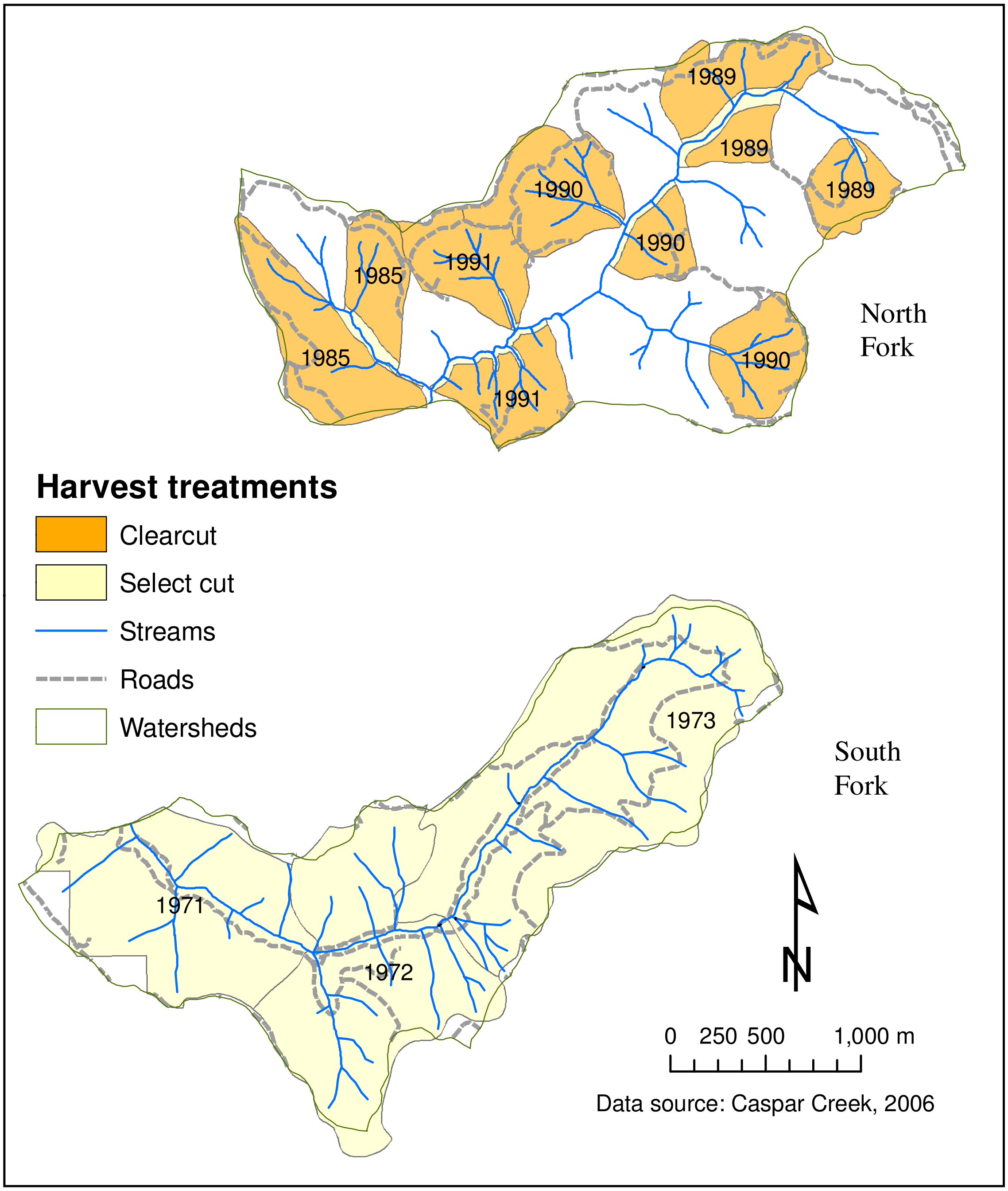


Figure3.2. The locations of timber harvests, streams, and roads for the North Fork and the South Fork watersheds at Caspar Creek, California for 1971 to 1991. Years indicate when a timber harvest occurred.

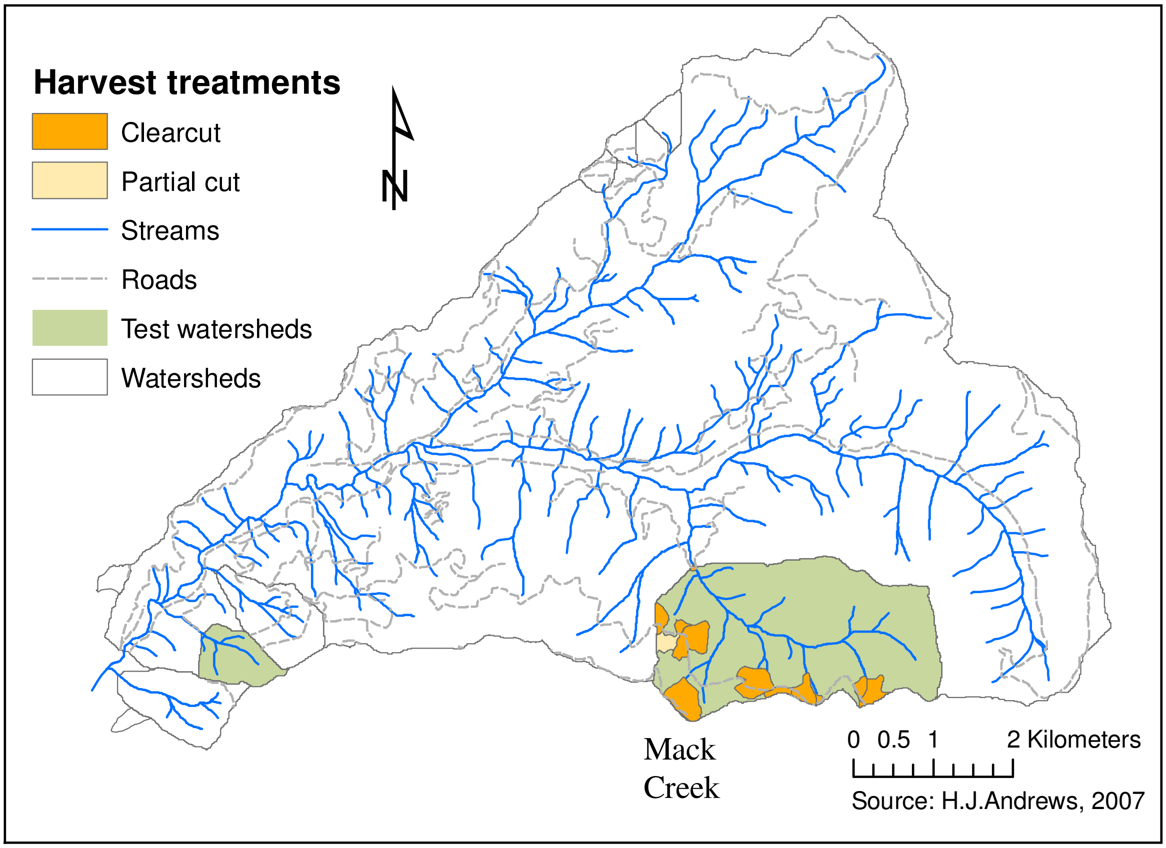


Figure 3.3. The locations of timber harvests, streams, and roads for Mack Creek and WS2 (control) at H.J. Andrews, Oregon.

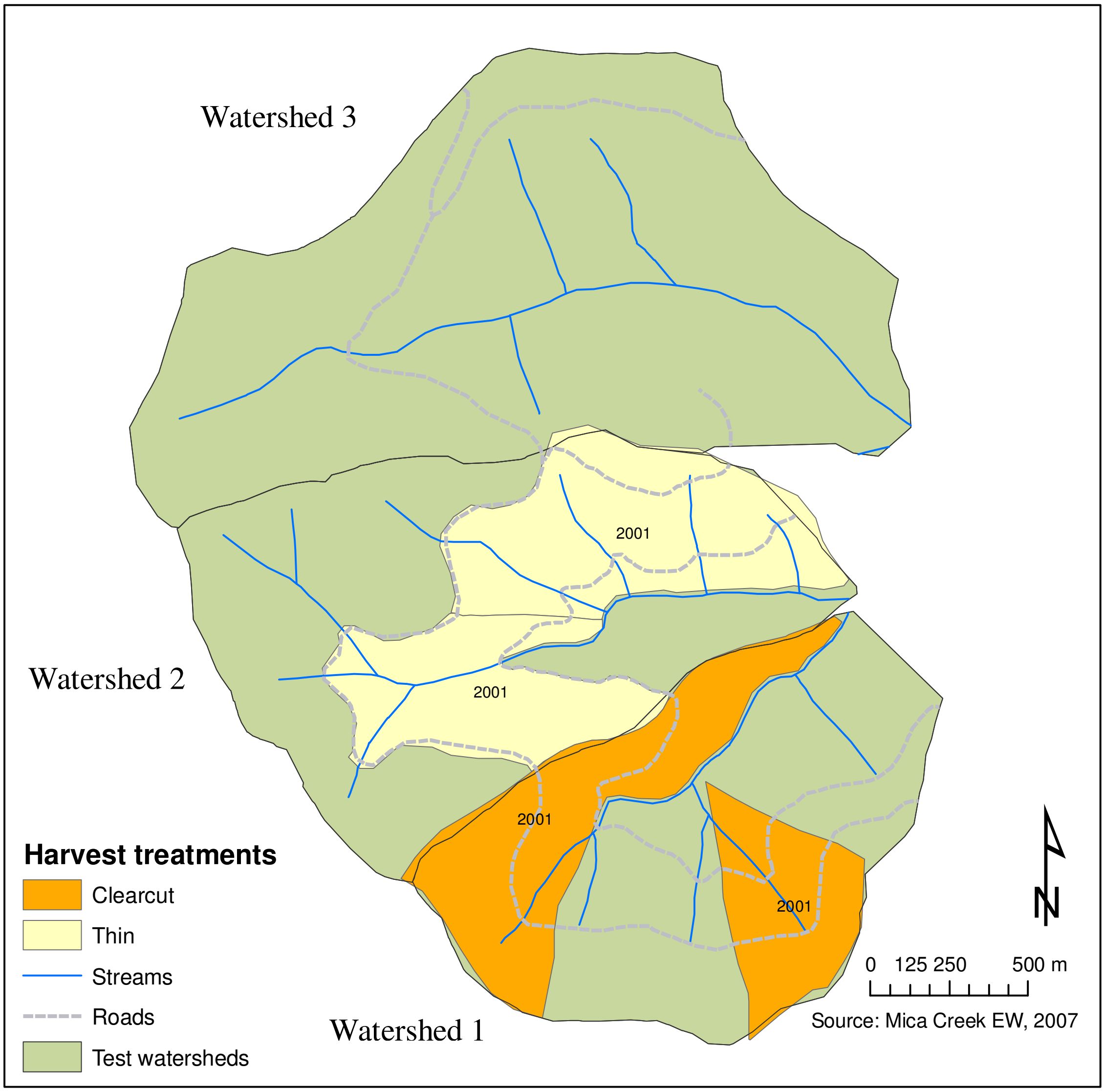


Figure 3.4. The locations of timber harvest, streams, and roads for Watersheds 1, 2, and 3 (control) at Mica Creek, Idaho. Years indicate when a timber harvest occurred.

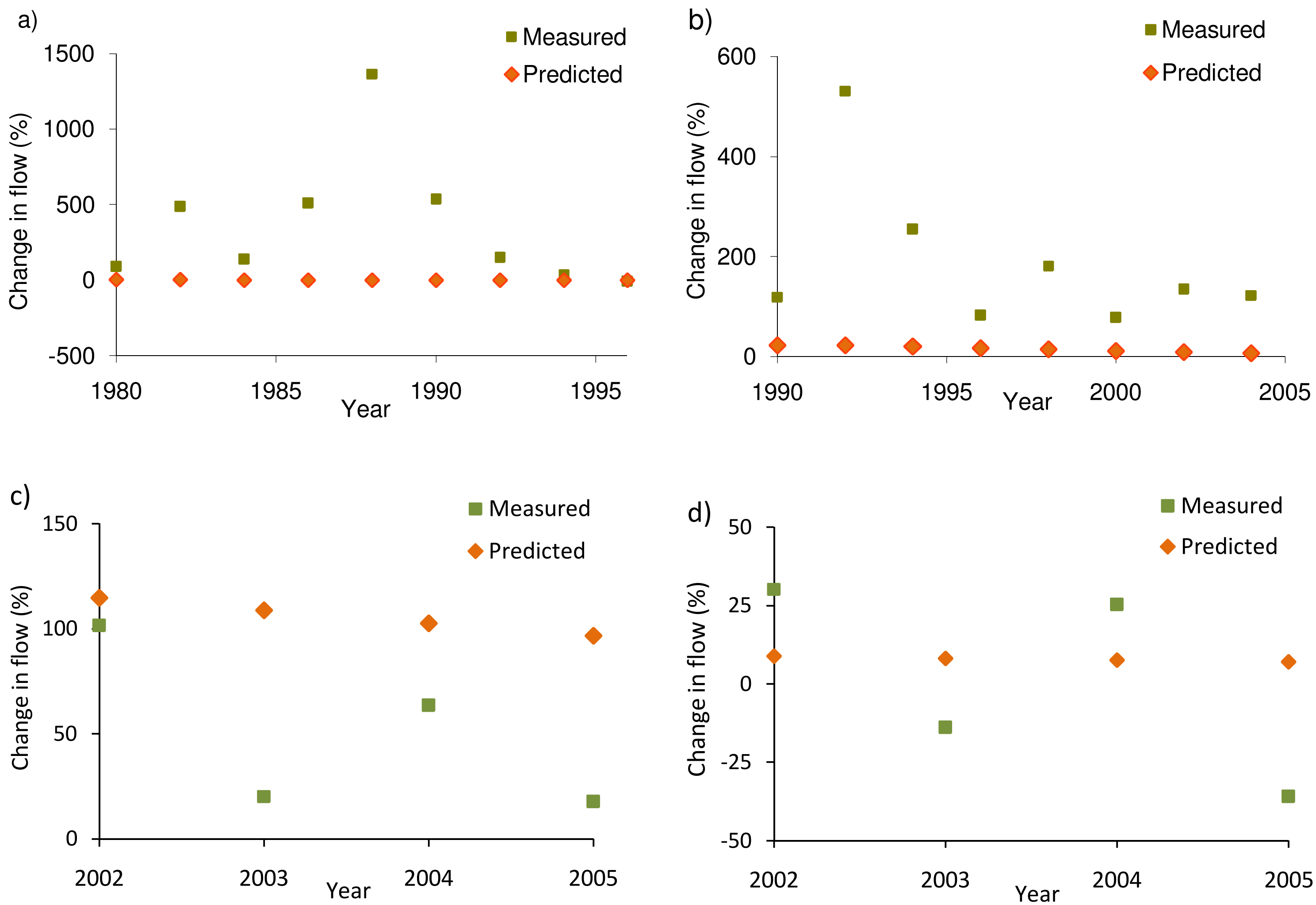


Figure 3.5. Comparison of predicted and measured changes in the 1st percentile flows for: a) Mack Creek at the H.J. Andrews, b) North Fork of Caspar Creek, c) Watershed 1 at Mica Creek, and d) Watershed 2 at Mica Creek.

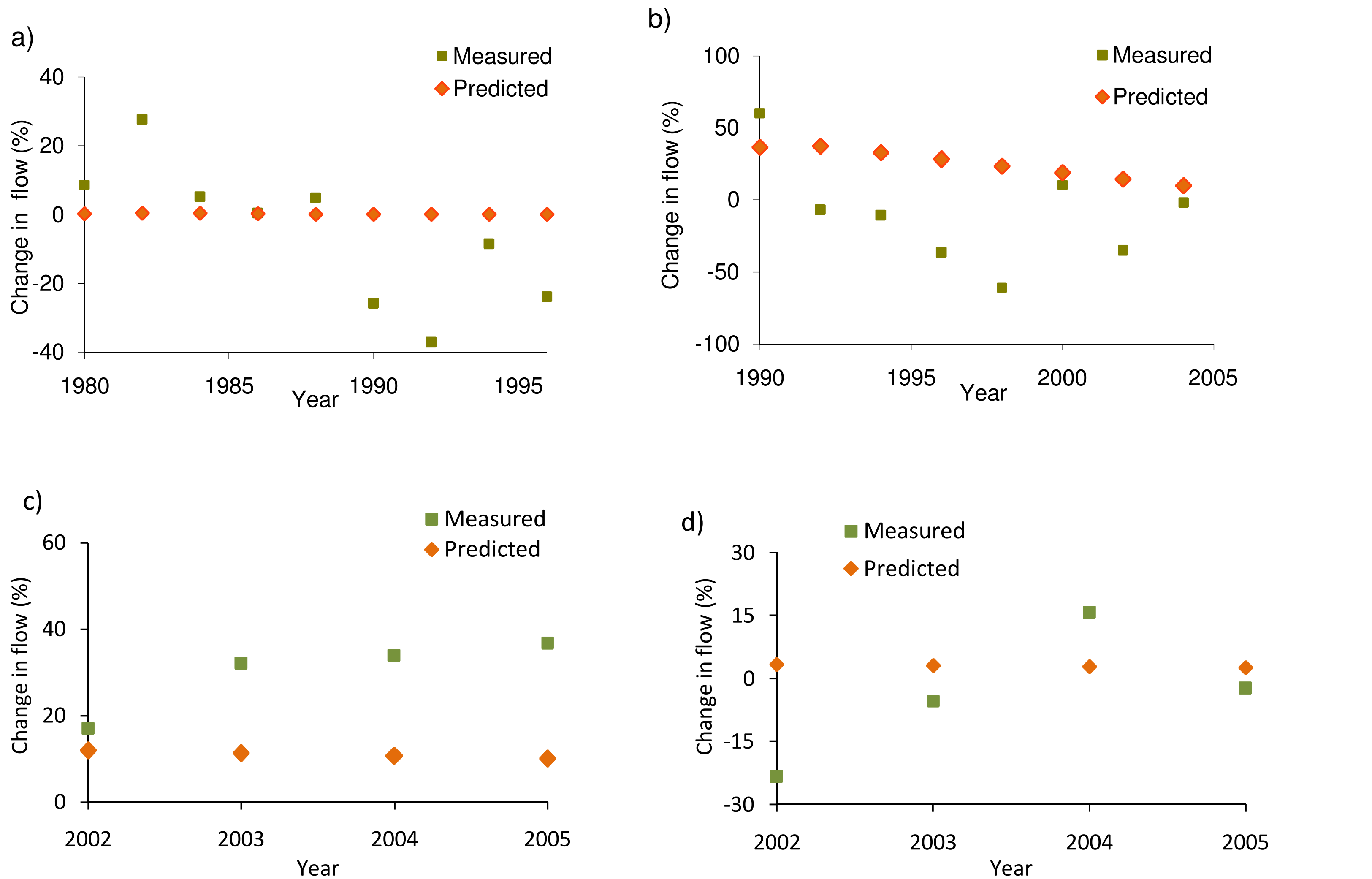


Figure 3.6. Comparison of predicted and measured changes for 50th percentile flows for: a) Mack Creek at the H.J. Andrews, b) North Fork of Caspar Creek, c) Watershed 1 at Mica Creek, and d) Watershed 2 at Mica Creek.

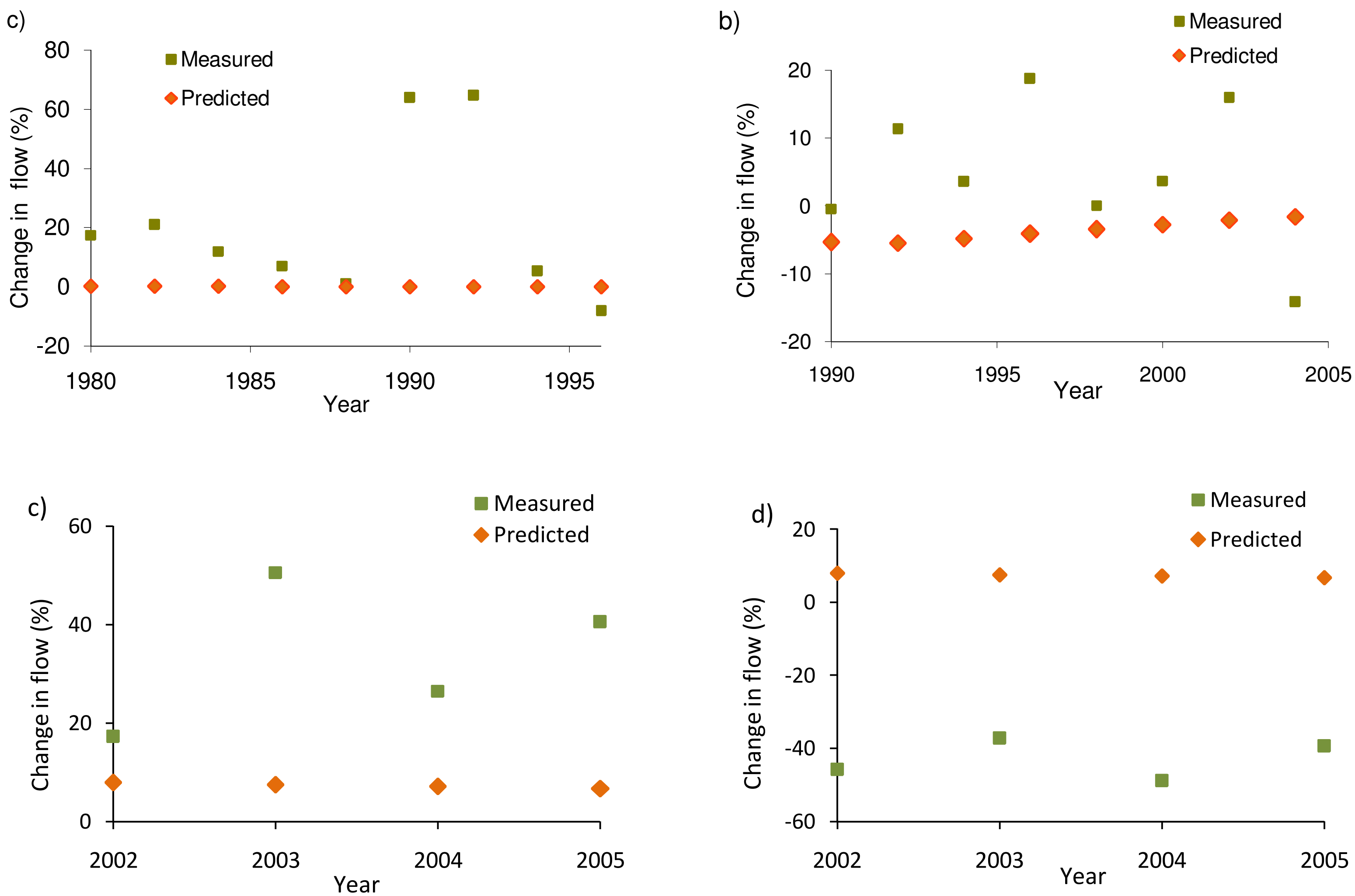


Figure 3.7. Comparison of predicted and measured changes for 99th percentile flows for: a) Mack Creek at the H.J. Andrews, b) North Fork of Caspar Creek, c) Watershed 1 at Mica Creek, and d) Watershed 2 at Mica Creek.

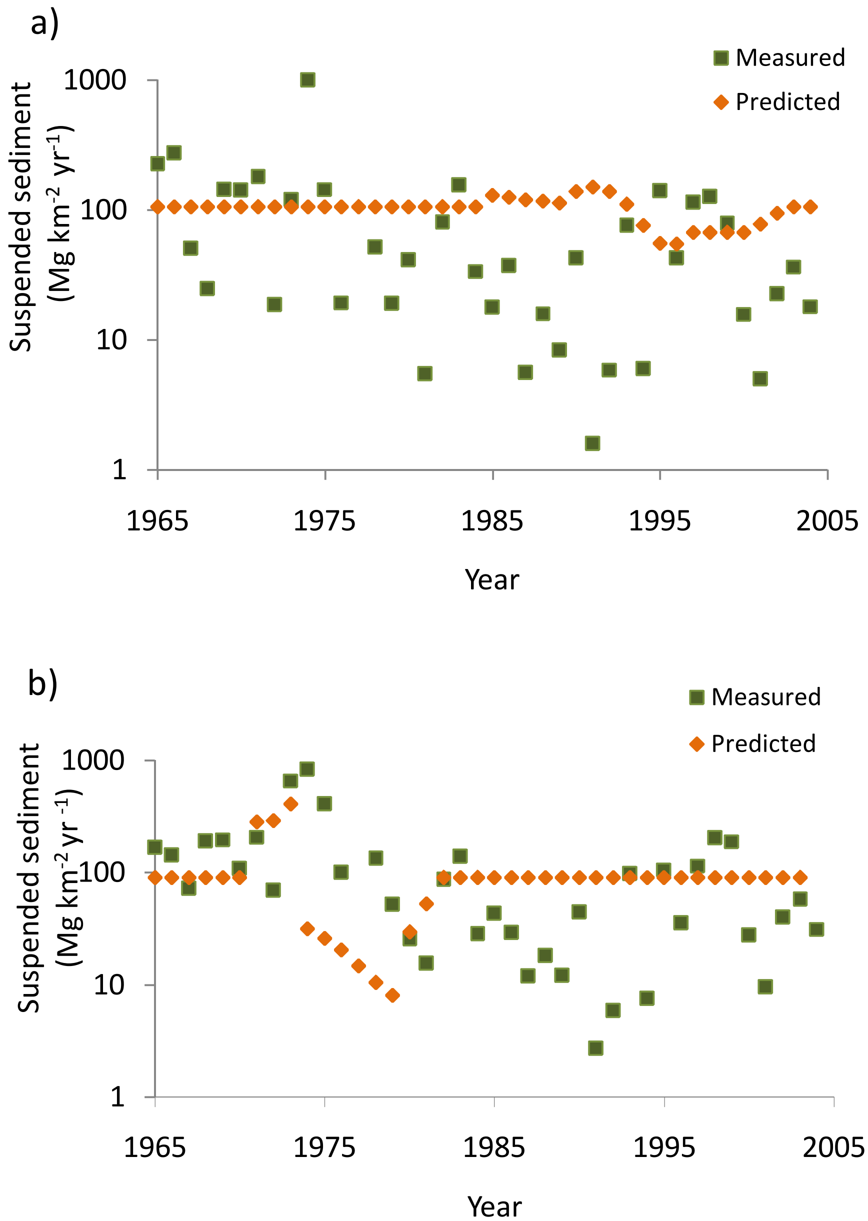


Figure 3.8. Predicted and measured annual suspended sediment yields for: a) the North Fork, and b) the South Fork at Caspar Creek from 1965 to 2004.

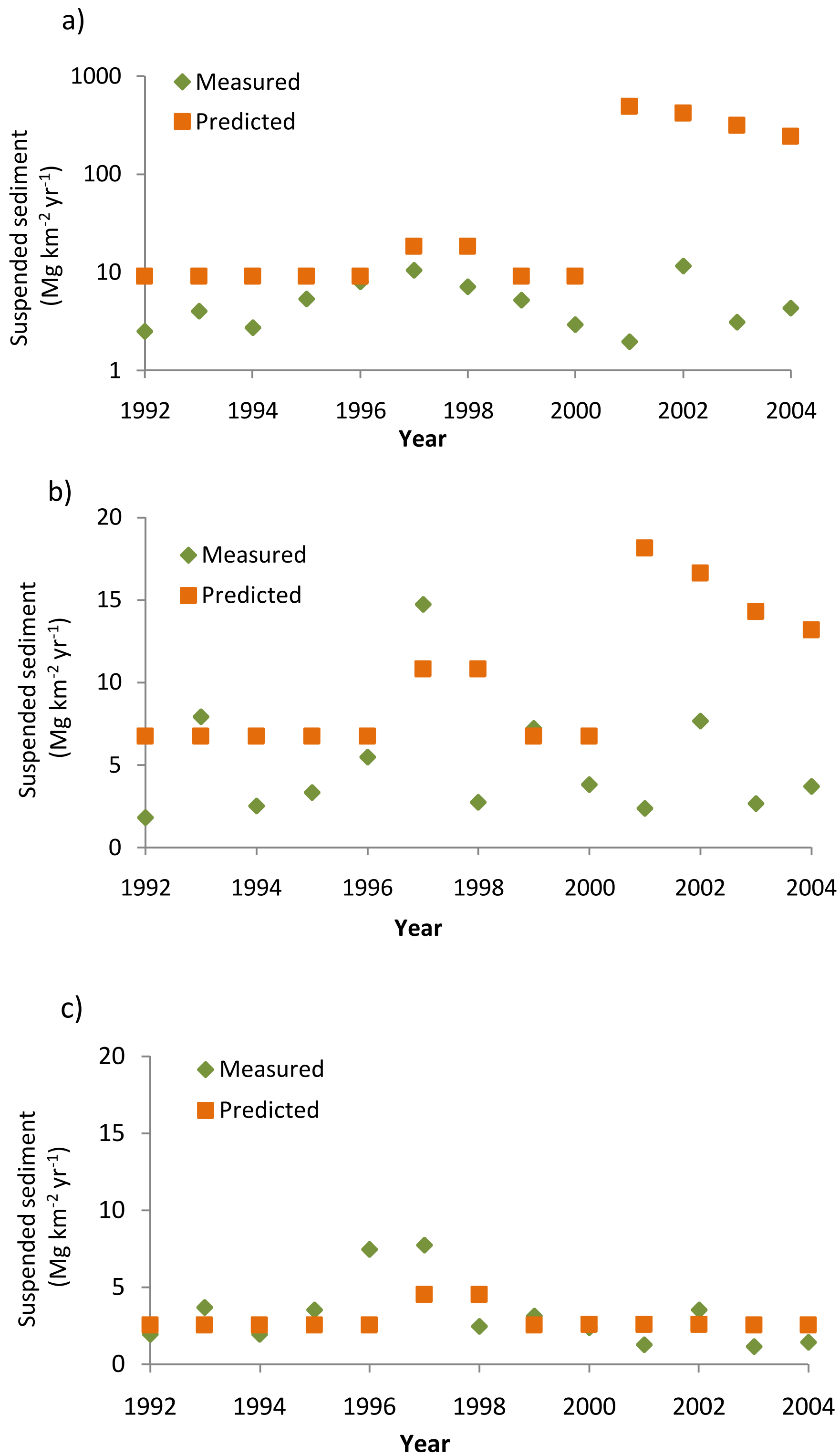
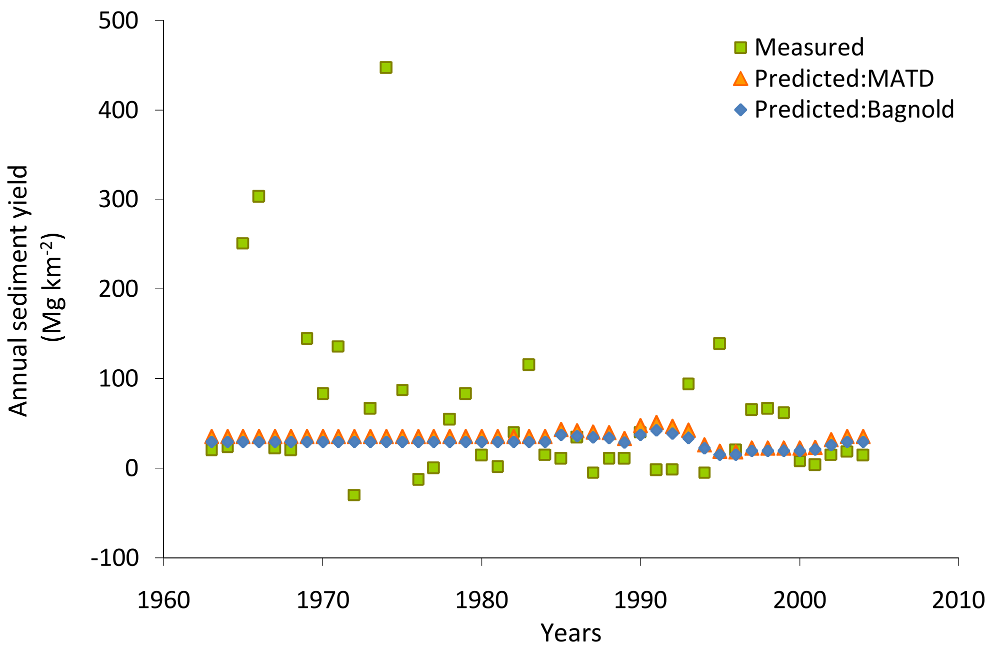


Figure 3.9. Predicted and measured annual suspended sediment yields for: a) Watershed 1, b) Watershed 2, and c) Watershed 3 at Mica Creek from 1992 to 2004.

a)



b)

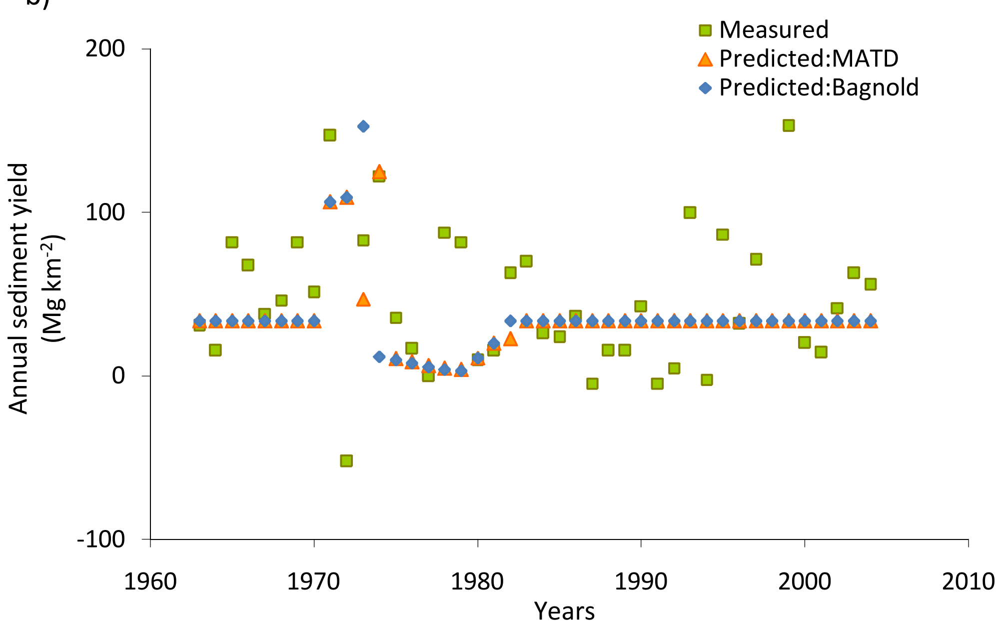


Figure 3.10. Predicted and measured annual bedload sediment yields using the mean annual travel distance (MATD) and Bagnold's equation for the a) North Fork and b) South Fork of Caspar Creek from 1963 to 2004.

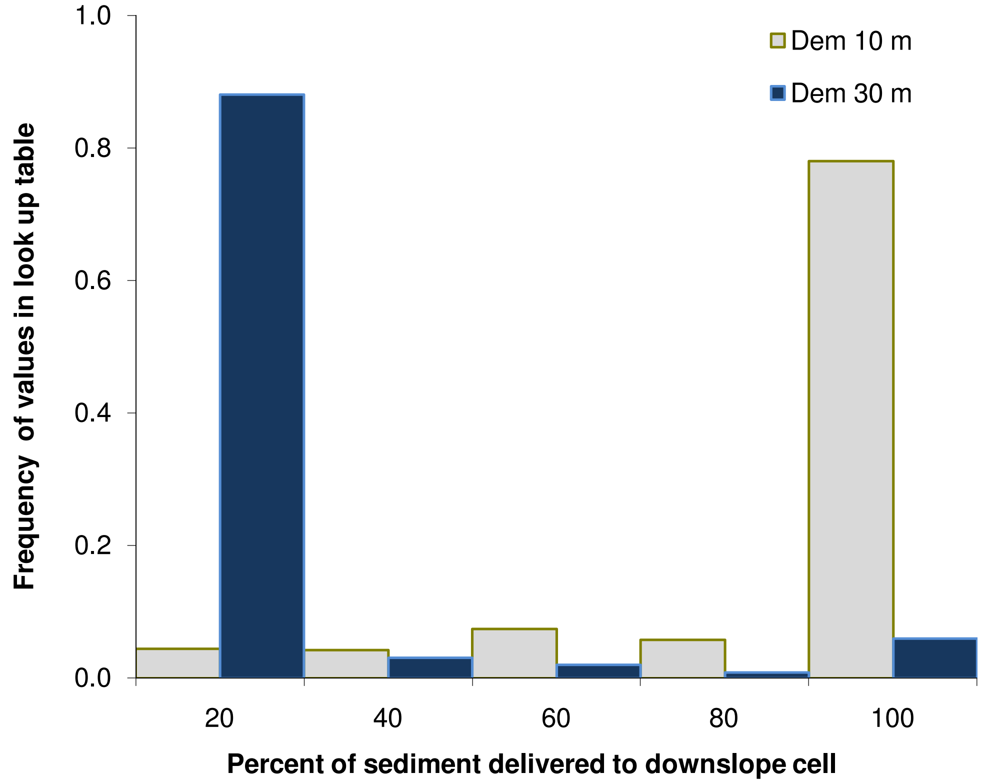
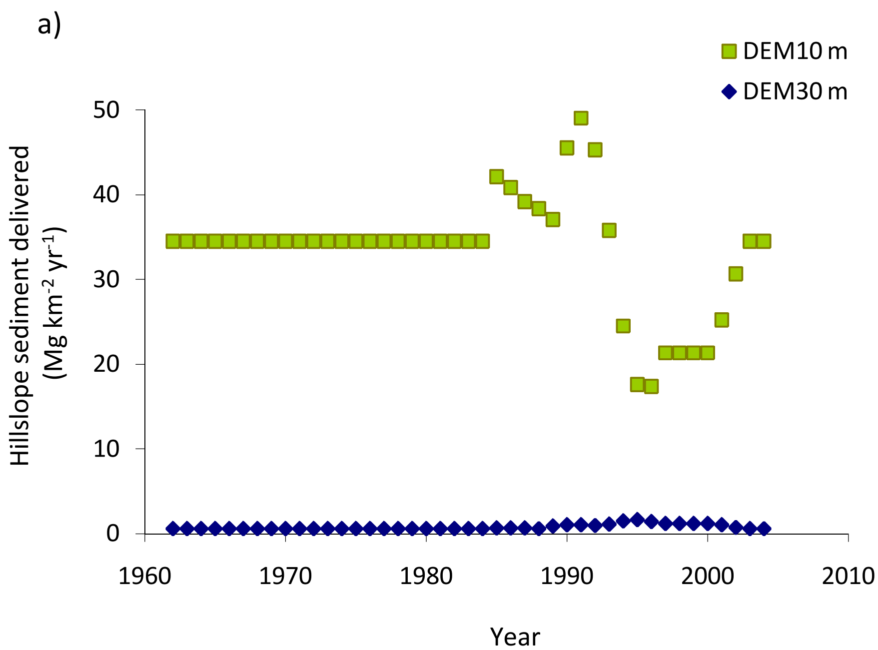


Figure 3.11. Frequency distribution of 588 hillslope sediment delivery values from the WEPP look up tables using 20 m and 60 m hillslopes that correspond to the10 m and 30 m DEMs, respectively. Both sets of simulations used the Caspar Creek climate in the WEPP database.



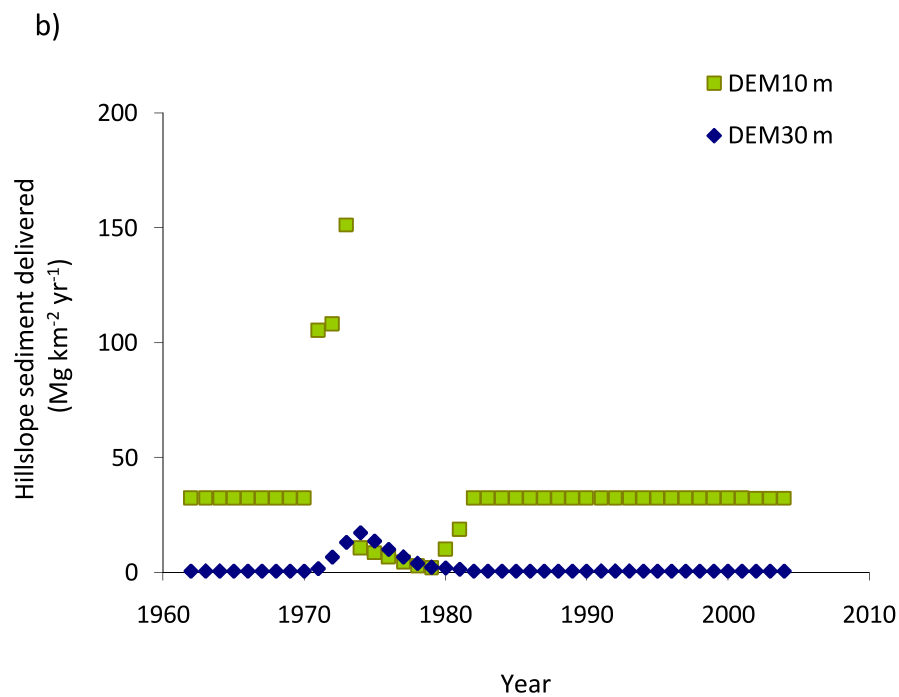


Figure 3.12. Calculated hillslope sediment delivery for a) the North Fork and b) the South Fork at Caspar Creek from 1962 to 2010 using look-up tables derived with 20- and 60-m hillslopes corresponding to10 and 30 m DEMs, respectively.

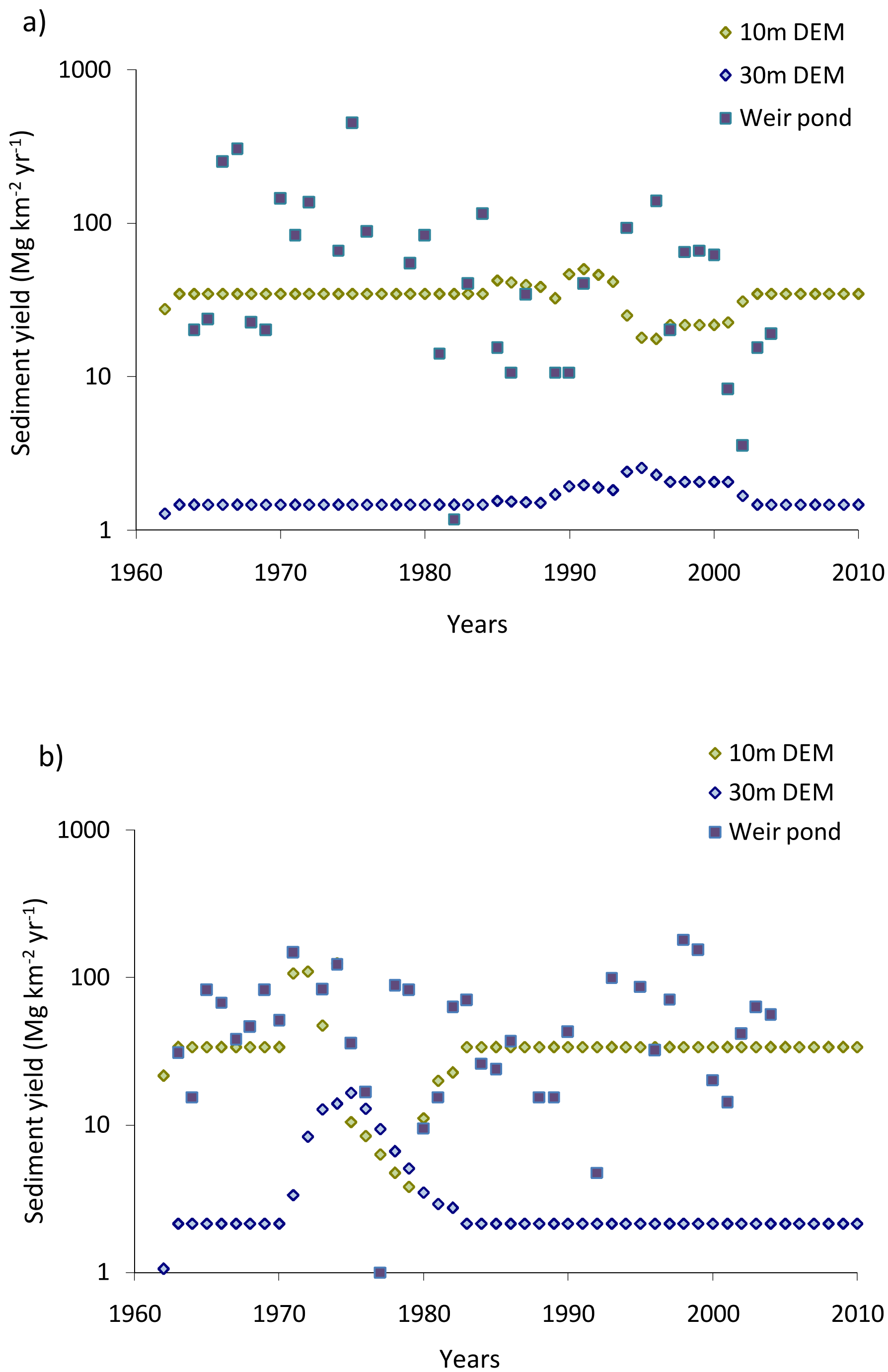


Figure 3.13. Sediment yields calculated using a mean annual travel distance of 2400 m for a) the North Fork and b) the South Fork at Caspar Creek. At each site simulations used either the look up table for 20 m hillslopes with the 10 m DEM or the look up table for 60 m hillslopes with the 30 m DEM.

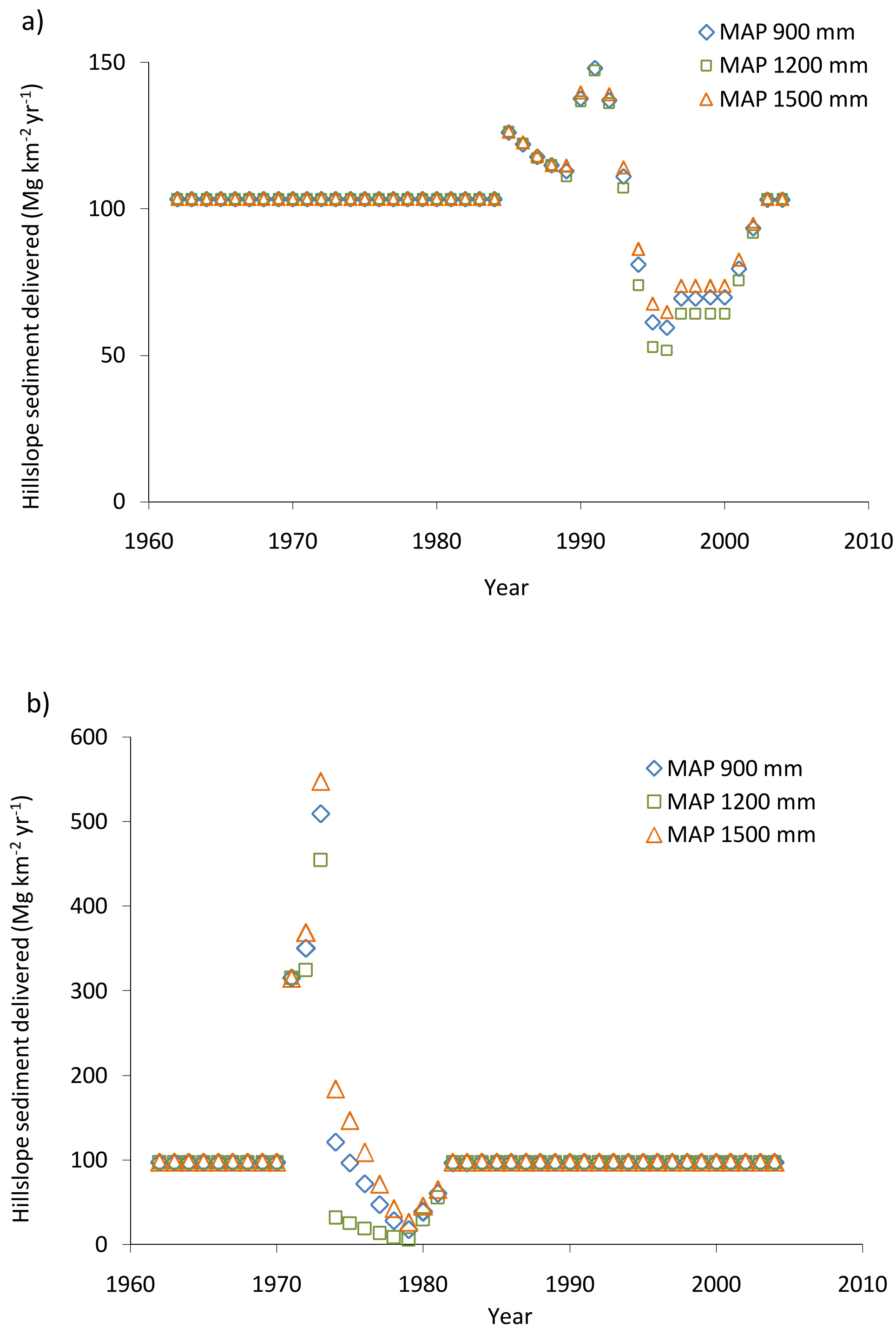


Figure 3.14. Changes in the amount of hillslope sediment delivered from hillslopes as the mean annual precipitation is varied from 900 to 1500 mm for a) the North Fork and b) the South Fork at Caspar Creek from 1962 to 2005.

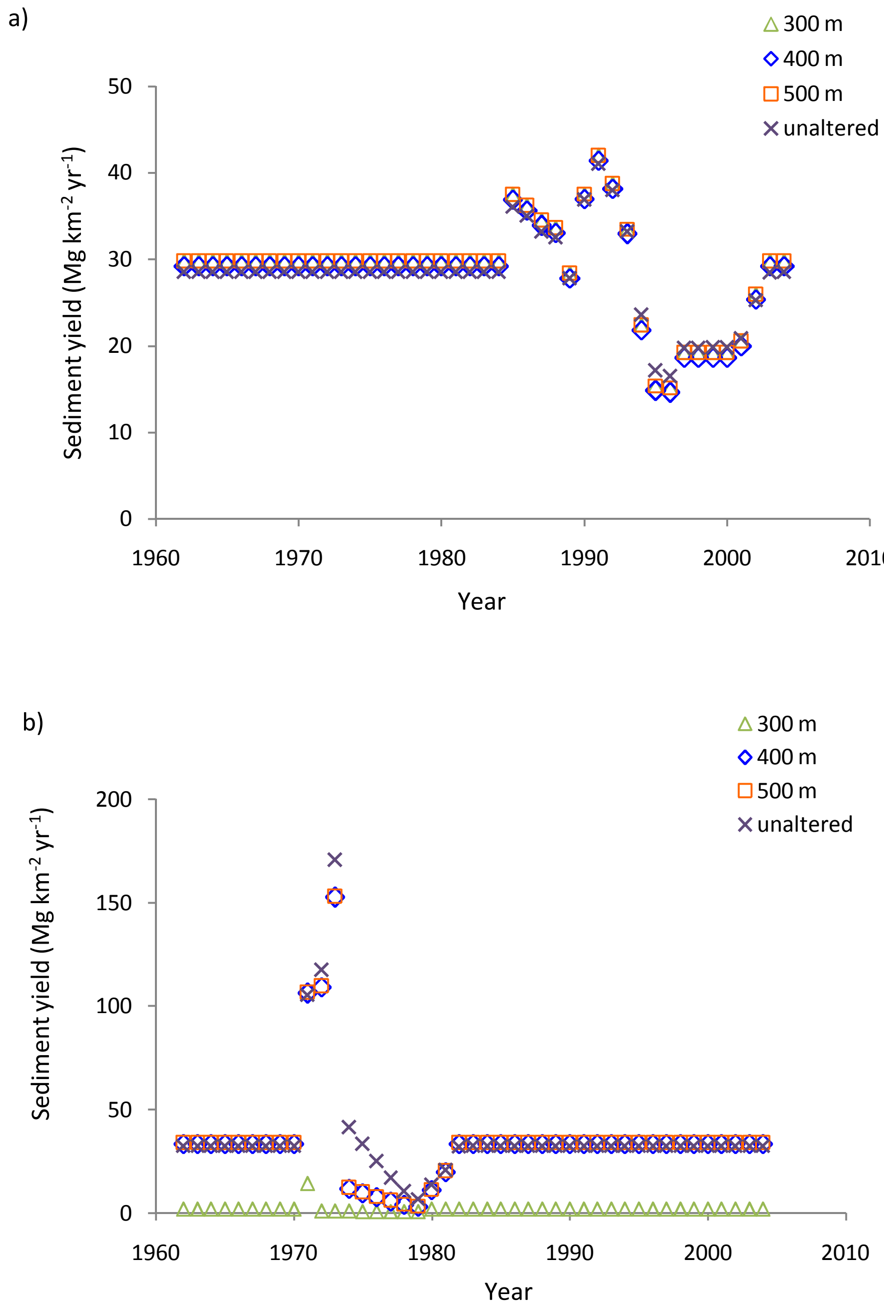


Figure 3.15. Changes in the amount of bedload sediment yields using Bagnold's method as the maximum stream length is varied from the unaltered lengths to 300, 400, and 500 m for a) the North Fork and b) the South Fork of Caspar Creek from 1962 to 2005. Maximum unaltered stream lengths ranged up to almost 2500 m.

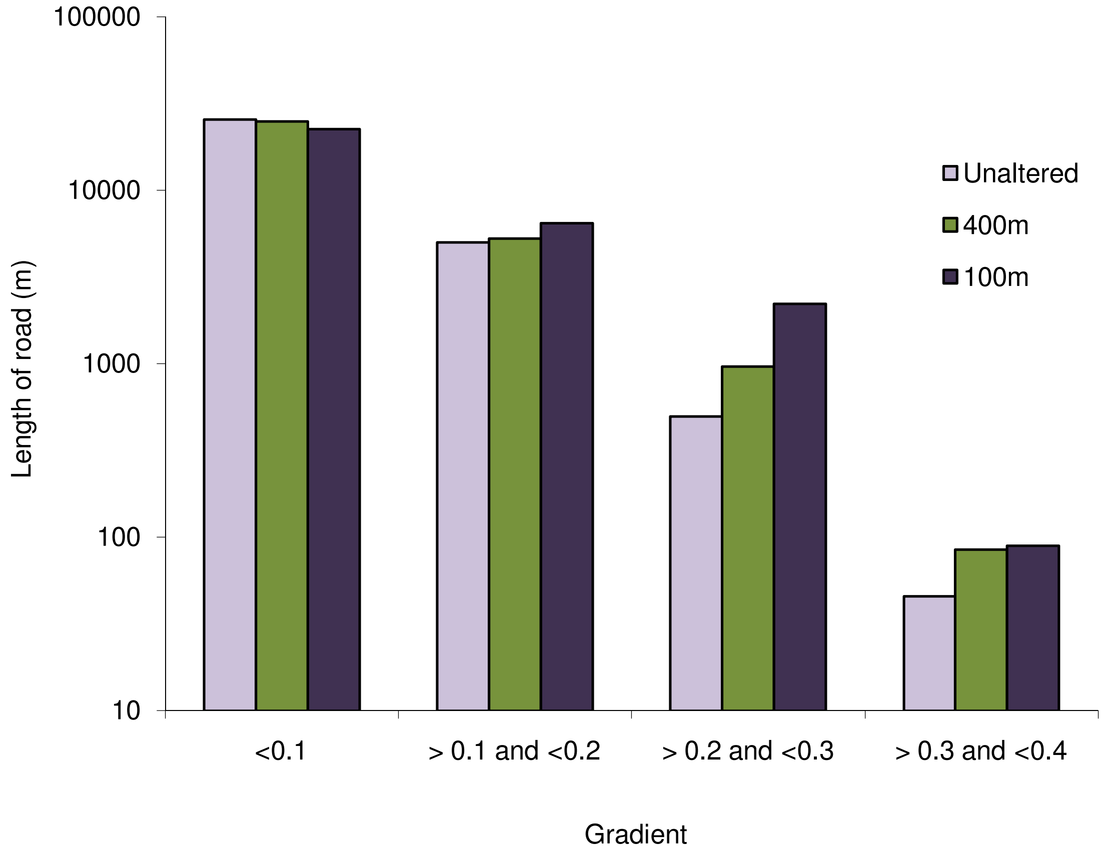


Figure 3.16. Comparison of road arcs length by gradients for unaltered road arcs, and roads with maximum arc lengths of 400 m and 100m.

Appendix A

Input and output data from 30 years of simulations and a silt loam soil using WEPP: Road for Mica Creek

Run number	Design	Surface, traffic	Road grad (%)	Road length (m)	Road width (m)	Fill grad (%)	Fill length (m)	Buffer grad (%)	Buffer length (m)	Rock content (%)	Average annual rain runoff (mm)	Average annual snow runoff (mm)	Average annual sediment leaving road (kg)	Average annual sediment leaving buffer (kg)
1	Outsloped, rutted	native low	0.3	50	4	50	5	25	10	20	1	4	13	5
2	Outsloped, rutted	native low	0.3	100	4	50	5	25	10	20	2	18	23	8
3	Outsloped, rutted	native low	0.3	150	4	50	5	25	10	20	2	33	46	17
4	Outsloped, rutted	native low	0.3	200	4	50	5	25	10	20	3	44	50	14
5	Outsloped, rutted	native low	0.3	250	4	50	5	25	10	20	4	52	63	18
6	Outsloped, rutted	native low	0.3	300	4	50	5	25	10	20	5	58	78	24
7	Outsloped, rutted	native low	1	50	4	50	5	25	10	20	8	10	50	22
8	Outsloped, rutted	native low	1	100	4	50	5	25	10	20	14	34	118	76
9	Outsloped, rutted	native low	1	150	4	50	5	25	10	20	19	62	191	140
10	Outsloped, rutted	native low	1	200	4	50	5	25	10	20	22	80	277	222
11	Outsloped, rutted	native low	1	250	4	50	5	25	10	20	23	95	357	314

Run number	Design	Surface, traffic	Road grad (%)	Road length (m)	Road width (m)	Fill grad (%)	Fill length (m)	Buffer grad (%)	Buffer length (m)	Rock content (%)	Average annual rain runoff (mm)	Average annual snow runoff (mm)	Average annual sediment leaving road (kg)	Average annual sediment leaving buffer (kg)
12	Outsloped, rutted	native low	1	300	4	50	5	25	10	20	26	103	446	406
13	Outsloped, rutted	native low	10	50	4	50	5	25	10	20	10	10	261	72
14	Outsloped, rutted	native low	10	100	4	50	5	25	10	20	20	37	1,259	471
15	Outsloped, rutted	native low	10	150	4	50	5	25	10	20	26	65	3,148	1,364
16	Outsloped, rutted	native low	10	200	4	50	5	25	10	20	31	86	5,795	2,758
17	Outsloped, rutted	native low	10	250	4	50	5	25	10	20	34	102	9,311	4,620
18	Outsloped, rutted	native low	10	300	4	50	5	25	10	20	37	115	13,399	7,005
19	Outsloped, rutted	native low	15	50	4	50	5	25	10	20	11	10	452	96
20	Outsloped, rutted	native low	15	100	4	50	5	25	10	20	20	36	2,234	669
21	Outsloped, rutted	native low	15	150	4	50	5	25	10	20	27	64	5,472	1,981
22	Outsloped, rutted	native low	15	200	4	50	5	25	10	20	32	87	9,992	3,976
23	Outsloped, rutted	native low	15	250	4	50	5	25	10	20	36	102	15,667	6,575
24	Outsloped, rutted	native low	15	300	4	50	5	25	10	20	39	116	22,344	9,897

Run number	Design	Surface, traffic	Road grad (%)	Road length (m)	Road width (m)	Fill grad (%)	Fill length (m)	Buffer grad (%)	Buffer length (m)	Rock content (%)	Average annual rain runoff (mm)	Average annual snow runoff (mm)	Average annual sediment leaving road (kg)	Average annual sediment leaving buffer (kg)
25	Outsloped, rutted	native high	0.3	50	4	50	5	25	10	20	1	4	14	5
26	Outsloped, rutted	native high	0.3	100	4	50	5	25	10	20	2	18	24	8
27	Outsloped, rutted	native high	0.3	150	4	50	5	25	10	20	2	33	47	17
28	Outsloped, rutted	native high	0.3	200	4	50	5	25	10	20	3	44	51	15
29	Outsloped, rutted	native high	0.3	250	4	50	5	25	10	20	4	52	64	18
30	Outsloped, rutted	native high	0.3	300	4	50	5	25	10	20	5	58	79	24
31	Outsloped, rutted	native high	1	50	4	50	5	25	10	20	8	10	61	33
32	Outsloped, rutted	native high	1	100	4	50	5	25	10	20	14	34	120	116
33	Outsloped, rutted	native high	1	150	4	50	5	25	10	20	19	62	181	217
34	Outsloped, rutted	native high	1	200	4	50	5	25	10	20	22	80	261	342
35	Outsloped, rutted	native high	1	250	4	50	5	25	10	20	23	95	346	487
36	Outsloped, rutted	native high	1	300	4	50	5	25	10	20	26	103	444	639
37	Outsloped, rutted	native high	10	50	4	50	5	25	10	20	10	10	922	201

Run number	Design	Surface, traffic	Road grad (%)	Road length (m)	Road width (m)	Fill grad (%)	Fill length (m)	Buffer grad (%)	Buffer length (m)	Rock content (%)	Average annual rain runoff (mm)	Average annual snow runoff (mm)	Average annual sediment leaving road (kg)	Average annual sediment leaving buffer (kg)
38	Outsloped, rutted	native high	10	100	4	50	5	25	10	20	20	37	4,572	1,417
39	Outsloped, rutted	native high	10	150	4	50	5	25	10	20	26	65	11,574	3,906
40	Outsloped, rutted	native high	10	200	4	50	5	25	10	20	31	86	21,224	7,581
41	Outsloped, rutted	native high	10	250	4	50	5	25	10	20	34	102	34,090	12,073
42	Outsloped, rutted	native high	10	300	4	50	5	25	10	20	37	115	49,033	17,771
43	Outsloped, rutted	native high	15	50	4	50	5	25	10	20	11	10	1,710	277
44	Outsloped, rutted	native high	15	100	4	50	5	25	10	20	20	36	8,536	1,871
45	Outsloped, rutted	native high	15	150	4	50	5	25	10	20	27	64	20,758	4,995
46	Outsloped, rutted	native high	15	200	4	50	5	25	10	20	32	87	37,521	9,307
47	Outsloped, rutted	native high	15	250	4	50	5	25	10	20	36	102	58,340	14,257
48	Outsloped, rutted	native high	15	300	4	50	5	25	10	20	39	116	82,579	20,365

Appendix B

Climate files

Climate data used for H.J. Andrews

Station: **ANDREWS, OR** CLIGEN VERSION 4.3

Latitude	Longitude	Elevation (m)	Obs. Years	Beginning year	Years simulated
44.21	-122.26	243	99	1	100

Observed monthly average max temperature (C)

5.7 8.7 11.1 14.9 18.9 22.8 27.5 27.4 23.9 17.3 9.7 6.0

Observed monthly average min temperature (C)

-3.1 -1.8 -0.7 1.2 4.0 7.2 8.6 8.0 5.3 2.4 0.1 -2.1

Observed monthly average solar radiation (Langleys/day)

108.0 181.1 313.6 446.5 554.7 609.4 681.8 576.7 425.9 262.7 153.4 93.1

Observed monthly average precipitation (mm)

154.8 120.9 118.0 81.3 66.7 49.2 15.0 25.2 42.6 90.3 161.6 183.1

Climate data used for 900 mm mean annual precipitation climate at Caspar Creek

Station: **Caspar900CA** CLIGEN VERSION 4.31

Latitude	Longitude	Elevation (m)	Obs. Years	Beginning year	Years simulated
39.41	123.76	204	45	1	100

Observed monthly average max temperature (C)

13.0 13.8 14.2 15.1 16.3 17.6 18.0 18.3 18.8 17.6 15.5 13.3

Observed monthly average min temperature (C)

4.1 4.9 5.4 6.2 7.6 9.1 9.6 9.9 9.6 8.3 6.4 4.6

Observed monthly average solar radiation (Langleys/day)

149.0 249.0 348.0 512.0 596.0 669.0 689.0 609.0 452.0 308.0 194.0 109.0

Observed monthly average precipitation (mm)

167.5 126.5 130.1 59.1 22.9 6.5 2.4 8.2 16.1 59.7 140.6 158.4

Climate data used for 1200 mm mean annual precipitation climate at Caspar Creek

Station: **Caspar1200CA** CLIGEN VERSION 4.31

Latitude	Longitude	Elevation (m)	Obs. Years	Beginning year	Years simulated
39.41	123.76	204	45	1	100

Observed monthly average max temperature (C)

13.0 13.8 14.2 15.1 16.3 17.6 18.0 18.3 18.8 17.6 15.5 13.3

Observed monthly average min temperature (C)

4.1 4.9 5.4 6.2 7.6 9.1 9.6 9.9 9.6 8.3 6.4 4.6

Observed monthly average solar radiation (Langleys/day)

149.0 249.0 348.0 512.0 596.0 669.0 689.0 609.0 452.0 308.0 194.0 109.0

Observed monthly average precipitation (mm)

223.3 171.0 172.2 79.5 29.4 8.3 3.0 10.5 21.5 81.1 188.6 212.4

Climate data used for 1500 mm mean annual precipitation climate at Caspar Creek

Station: **Caspar1500CA** CLIGEN VERSION 4.31

Latitude	Longitude	Elevation (m)	Obs. Years	Beginning year	Years simulated
39.41	123.76	204	45	1	100

Observed monthly average max temperature (C)

13.0 13.8 14.2 15.1 16.3 17.6 18.0 18.3 18.8 17.6 15.5 13.3

Observed monthly average min temperature (C)

4.1 4.9 5.4 6.2 7.6 9.1 9.6 9.9 9.6 8.3 6.4 4.6

Observed monthly average solar radiation (Langleys/day)

149.0 249.0 348.0 512.0 596.0 669.0 689.0 609.0 452.0 308.0 194.0 109.0

Observed monthly average precipitation (mm)

279.2 215.4 214.4 100.0 37.6 10.2 3.6 12.9 26.9 100.2 236.6 266.5

Climate data used for Mica Creek

Station: **MicaCreekID** CLIGEN VERSION 4.31

Latitude Longitude Elevation (m) Obs. Years Beginning year Years simulated

47.15 116.27 1414 45 1 100

Observed monthly average max temperature (C)

0.5 3.9 7.2 12.4 17.5 21.7 26.9 26.8 21.3 14.4 5.5 1.1

Observed monthly average min temperature (C)

-7.8 -5.6 -3.8 -0.3 3.3 6.8 8.6 8.2 4.4 0.6 -2.7 -6.0

Observed monthly average solar radiation (Langleys/day)

125.0 212.0 332.0 455.0 548.0 602.0 661.0 547.0 405.0 241.0 141.0 91.0

Observed monthly average precipitation (mm)

198.3 150.2 140.0 100.2 103.0 87.9 39.9

Chapter 4 Sediment delivery pathways from harvest units to streams

4.1 Abstract

Timber harvest is typically the largest area of disturbance in forested watersheds, and harvested areas may generate from one to five times more erosion than undisturbed areas (Motha *et al.*, 2003). Sediment from harvested areas becomes a problem when it reaches stream channels as it can degrade water quality and aquatic habitat, alter channel morphology, and reduce reservoir storage capacity. Streamside management zones (SMZs) are often prescribed, but there is little information about the delivery of runoff and sediment through these zones. Hence the objectives of this study were to: 1) determine the frequency of sediment pathways in the form of rills and sediment plumes coming from timber harvest units; 2) measure the connectivity and other physical characteristics of the sediment pathways; and 3) develop models to predict the length and connectivity of rills and sediment plumes from harvest units to streams.

Nearly 200 harvest units with streamside management zones were assessed on four National Forests in the central and northern Sierra Nevada Mountains of California. In each unit the upslope edge of the SMZ was systematically traversed to identify the erosional and depositional features originating from the harvest unit; features initiated by roads or burned areas were excluded. The data collected for each feature included feature type, length, depth,

width, years since harvest, hillslope gradient, surface roughness, mean annual precipitation, soil type, and hillslope aspect. Features were classified as connected when they came within 10 m of a stream channel.

Nineteen features were found in SMZs below harvest units ranging in age from 2 to 18 years. Features lengths ranged from 10 to 220 m, and the length was significantly related to mean annual precipitation, cosine of the aspect, elevation, and hillslope gradient (R^2 = 64%, p = 0.004). Six of the nineteen features were connected to streams and five of the six connected features originated from skid trails. The results indicate that timber harvest alone rarely initiated large amounts of surface runoff and surface erosion, particularly when newer harvest practices were utilized. Sediment delivery from timber harvest may be further reduced by locating skid trails away from streams, constructing more frequent water bars, maintaining high surface roughness downslope of water bars, and decommissioning skid trails promptly and carefully.

4.2 Introduction

Anthropogenic sediment sources on forested hillslopes include roads, skid trails, and timber harvest units (e.g., Megahan, 1972; Beschta, 1978; Croke *et al.,* 1999; Barrett and Conroy, 2001; Motha *et al.*, 2003). Most recent research has focused on roads (e.g., Luce and Black, 1999; Jones *et al.*, 2000; Lane and Sheridan, 2002; Coe, 2006), but timber harvest units represent the largest areas of disturbance and can increase erosion rates by one to five times relative to undisturbed areas (Motha *et al.*, 2003).

The delivery of overland flow and sediment from disturbed hillslopes contributes to cumulative effects such as the alteration of channel morphology (Troendle and Olson, 1994, Madej and Ozaki, 1998), degradation of aquatic habitat (Shaw and Richardson, 2001), reductions in reservoir storage, and increases in pollutant transport (EPA, 2003). When sediment is delivered from hillslope sources to the stream network and the watershed outlet this is defined as sediment connectivity (Bracken and Croke, 2007). Connectivity of sediment pathways can be in the form of sediment plumes when there is an excess of sediment relative to overland flow, or in the form of rills when the transport capacity is greater than the sediment load. Rills and sediment plumes are collectively described as features in this paper.

In recent years forest management techniques have been modified to minimize surface runoff, erosion, and connectivity. Skid trails are often designed to follow hillslope contours (Kreutzweiser and Capell, 2001). Undisturbed stream management zones (SMZs) are intended to provide vegetative roughness and high infiltration rates (Hairsine *et al*., 2002) that slow or absorb overland flow and filter sediment out of overland flow before the sediment reaches the stream network or water body (Kreutzweiser and Capell, 2001). "Breakthroughs" have been defined as the geomorphic features resulting from overland flow and sediment delivery from forest harvest units. These can penetrate SMZs and connect harvest units to the stream (Lacey, 2000; Rivenbark and Jackson, 2004). In the Georgia Piedmont, USA, there was an average of one breakthrough for every 20 acres of clearcut and site prepared land (Rivenbark and Jackson, 2004). Breakthroughs have been associated with convergent topography, steeper slopes, larger contributing areas, and less ground cover (Lacey, 2000; Rivenbark and Jackson, 2004). In Australia buffer zones 10 m wide reduced sediment delivery from skid trails to streams by 95% (Lacey, 2000).

Measuring and modeling connectivity and sediment delivery are critical for quantifying and predicting the cumulative effects of timber harvest activities in forested watersheds (Bracken and Croke, 2007). The fieldwork described in this paper evaluated whether the areas disturbed by timber harvest and skid trails are connected to stream channels by rills and sediment plumes. The specific objectives were to: 1) determine the proportion of timber harvest units with rills or sediment plumes; 2) measure the site characteristics, size, and connectivity of rills and plumes to stream channels; and 3) develop models to predict the length and connectivity of rills and sediment plumes from harvest units.

4.3 Study area

The study area included selected timber harvest units on the Eldorado, Lassen, Plumas, and Tahoe National Forests (NF) in the Sierra Nevada mountains of California (Figure 4.1). The Mediterranean climate in the northern Sierra Nevada is influenced by the high elevations of the Sierra Nevada Range and moist air flows from the Pacific Ocean. Mean annual precipitation ranges from as little as 370 mm on the east side to as much as 2000 mm on the west side (Teale, 1997). Ninety-five percent of the precipitation occurs during the winter wet season, and above 1500 m the precipitation falls mostly as snow (USDA Forest Service, 1986). Summer convective thunderstorms occur more frequently on the east side of the Sierra Nevada than on the west side (USDA Forest Service, 1983).

Forests on the west side are composed primarily of ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), Douglas fir (*Pseudotsuga menziesii*), red fir (*Abies magnifica*), white fir (*Abies concolor*), and incense cedar (*Libocedrus decurrens*). The dominant understory shrubs are green leaf manzanita (*Arctostaphylos patula*), huckleberry oak (*Quercus vaccinifolia*) and mountain whitethorn (*Ceanothus cordulatus*). Forests on the drier east side consist primarily of ponderosa pine, Jeffrey pine (*Pinus jeffreyi*), and white fir, with some lodgepole pine (*Pinus contorta*), western juniper (*Juniperus occidentalis*), and black oak (*Quercus kelloggii*). Most forest harvest takes place on soils weathered from andesitic, granitic, and meta-sedimentary material (USDA Forest Service, 1983; USDA Forest Service, 1986; USDA Forest Service, 2002).

4.4 Methods

The study was conducted on the four NFs with higher levels of timber harvest than the other 18 NFs in Region 5 of the USDA Forest Service (USFS). Most of the recent timber management projects in the Sierra Nevada tend to be larger-scale projects of about five hundred to several thousand hectares. Individual harvest units within these project areas average 15 hectares with a general range of 1 to 80 hectares (S. Tangenberg, USFS, pers. comm. February, 2008). Units that were harvested more than ten years ago were clearcut while newer units were generally subjected to thinning or group select cuts.

Harvest projects with erosion and sedimentation problems were identified by direct discussions with USFS personnel and by querying the USFS Best Management Practices Evaluation Program (BMPEP) database (USDA, 2004). The BMPEP provides 29 standardized forms for USFS personnel to evaluate the effects of engineering, grazing, mining, prescribed fires, roads, recreation, timber harvest, and vegetation on soils, runoff, erosion and streams. Data from about 3,000 evaluations were available for this research. This approach to identifying harvest projects was used to increase the likelihood of finding rills and sediment plumes and thereby obtain an adequate sample size for modeling purposes. The resulting bias in data collection does not affect the key findings and conclusions presented later.

Maps of each timber harvest project were obtained from the responsible NF and used to identify harvest units that were immediately upslope of stream channels. The lower edges of the selected harvest units were traversed on foot to identify all rills, gullies and sediment plumes entering SMZs. USFS policy requires SMZs that are 90 m wide along perennial streams and 45 m wide along ephemeral and intermittent streams. Harvesting and machinery are not allowed within SMZs, although we did observe some caterpillar tracks and skid trails crossing the SMZs.

A set of criteria was established to ensure that the erosional features being measured were only due to forest harvest activities. Fire salvage projects and projects that had burned since harvest were excluded because the effects of burning could not be separated from the effects of timber harvest. Features initiated by paved and unpaved roads were excluded; features initiated by skid trails were included. Features that ended at a road or that were extended by road drainage were excluded because we could not determine the length that a feature would have attained in the absence of the road. A minimum feature length of 10 m was used because this is the highest resolution of the digital elevation models (DEMs) being used to model cumulative effects.

When a feature was found, the following data were obtained: years since harvest, mean annual precipitation (MAP), soil depth, soil erodibility (K), straight line and feature lengths, feature gradient, aspect, elevation, hillslope gradient, hillslope curvature, surface roughness, and whether or not the feature was connected. A feature was classified as connected if it extended to within 10 m of a stream channel, indicating that some runoff and sediment will be delivered to the stream channel during the more extreme events (Croke and Mockler, 2001). The years since harvest was determined from project documents or estimated from vegetation regrowth. MAP at 127 mm intervals was obtained from statewide data (Teale, 1997) since not all NFs had isohyetal maps. Soil depth and erodibility were collected from the soil surveys for each NF. Harvest type was not available for every unit although we estimated that units older than ten years were clearcut and units harvested more recently were thinned or subjected to group selection. Hence age of harvest was used as a variable instead of harvest type for analysis.

Feature length was measured with a flexible tape. Feature gradient was measured in the field using a clinometer and aspect was measured with a compass. The cosine of the aspect was used to convert degrees from circular (0 to 360°) to continuous form for statistical analysis. Elevation, hillslope gradient and curvature were derived from 10 m digital elevation models (DEMs) obtained from each NF. Surface roughness was classified into one of five categories (Table 4.1). Current surface roughness was classified since past conditions could not be reliably determined. The drainage area that contributed to the feature was not determined because in many cases the contributing area could not be reliably identified or the area had been subsequently disturbed by management activities.

Each rill or sediment plume was divided into 10 m segments beginning at the upslope end. For each segment the gradient was measured with a clinometer and the surface roughness was estimated following Table 4.1. For each rill segment the mean depth was measured and Manning's roughness coefficient (n) was estimated. The discharge for each segment was calculated using Manning's equation:

$$Q = \frac{R^{2/3} * S^{1/2} * A}{n} \qquad \text{(Equation 4.1)}$$

where Q is the discharge ($m^3\ s^{-1}$), R is the hydraulic radius (m) approximated by mean rill depth, S is the energy gradient (m/m) approximated by the rill gradient, and A is the cross-sectional area (m^2).

4.4.1 Data analysis

The data set consisted of the predictor variables characterizing the rills and sediment plumes plus two response variables: feature length and connectivity class. T-tests were conducted on rill and plume lengths and slopes to determine if they were significantly different. As the rill and plume lengths were not significantly different, further analyses grouped the two types of features. Feature lengths were transformed to log base 10 to obtain a normal distribution (Ott and Longnecker, 2001). Linear regression was used to assess the relationship between each predictor variable and the log-transformed length, and a Pearson correlation matrix was calculated to test for association between predictor variables (Ott and Longnecker, 2001). Linear regression was used to determine whether feature segment slopes varied with distance along the rill.

The predictor variables that were more strongly correlated with feature length were then used to develop multivariate linear regression models to predict feature length. Models were selected according to the overall R^2 and Mallow's C(p). Using Mallow's C(p), the best fit model is the model where $|C(p) - p|$ is closest to zero and p is the number of parameters including the interception point (Ott and Longnecker, 2001). Partial R^2 values were calculated for each variable included in the models.

4.5 Results

Approximately 290 km were walked along the lower boundary of 200 harvest units. A total of 19 features, 15 rills and four sediment plumes were found. Fourteen or 7% of the harvest units had at least one rill or sediment plume entering into the SMZ, while five units had two features each (Table 4.2). Sixteen of the 19 features originated from skid trails.

The mean rill length was 43 m (s.d. = 54 m) and the range was from 11 m to 220 m. The median rill length was only 22 m or 50% of the mean, indicating a highly skewed distribution. In contrast, the median sediment plume length was only 17 m (s.d. = 5 m) and the lengths only varied from 10 m to 22 m (Figure 4.2). Three out of four plumes were within the 10 to 19 m range while only 50% of rills were within 10 and 19 m. The high variability means that there was no significant difference between the length of the rills and the length of the sediment plumes ($p=0.093$).

The rills occurred on hillslopes with gradients ranging from 9% to 36%, and the sediment plumes occurred on hillslopes with gradients ranging from 7% to 30%. The mean gradient for the rills of 20% is similar to the mean gradient of 21% for the plumes, and the feature gradients were generally similar to the hillslope gradients (Table 4.2). There was no difference in the mean gradient of rills and plumes ($p = 0.88$), or in the hillslope gradients where these features were found ($p = 0.77$). The lack of any significant difference in the lengths or slopes of the rills and sediment plumes means that these features were lumped for further analyses.

Log transformed feature length was significantly related to MAP ($r^2 = 0.45$, $p = 0.002$; Figure 4.3) and years since harvest ($r^2 = 0.34$, $p = 0.009$). The three longest features drove both of these relationships, as all three were in area with high MAP and on 18-year old clearcut units (Figure 4.4). If these three features are excluded, MAP was not significantly related to feature length.

Feature lengths tended to increase on steeper hillslopes, but this relationship was only weak ($r^2 = 0.15$, $p = 0.10$). All of the features were on hillslopes with low to moderate surface roughness (classes 1-3 in Table 4.1). Cosine (aspect), soil erodibility, soil depth, and the other independent variables were not significantly related to feature length.

The strongest correlations amongst the predictor variables were the inverse relationships between MAP and soil erodibility ($r = - 0.58$, $p = 0.01$), cosine (aspect) and soil depth ($r = -0.55$, $p = 0.01$), and the positive relationship between MAP and years since harvest ($r = 0.54$, $p = 0.02$) (Table 4.3). Soil erodibility is a function of soil texture, structure, organic matter, and permeability, and the presence of more organic matter generally decreases soil erosion (Renard *et al.*, 1997). Hence the inverse relationship between MAP and soil erodibility could stem from the presence of denser vegetation in areas of higher MAP as this would increase litter and soil organic matter, and decrease erosion. The negative relationship between aspect and soil depth indicates that soil tended to be deeper on north-facing slopes where the presence of denser vegetation and organic matter would protect the soil from surface runoff and presumably decrease erosion. MAP often increases with elevation, but for the fourteen sites with features, these two variables were only weakly correlated ($r = 0.44$, $p = 0.06$) (Table 4.3). This weak relationship can be attributed to the confounding effect of the rain shadow on the eastern side of the Sierra Nevada and relatively small range of elevations where the features were found (1536-1852 m). All variables were used in further analysis and model development as the strongest correlation between any two independent variables was only -0.58.

The best model for feature length (L) included MAP, hillslope gradient (S in m/m), cosine of the aspect (cosA), and elevation (E in meters) (Equation 4.2).

$$\text{Log } L = 1.852 + 0.0009 * MAP + 0.0104 * S - 0.2419 * \cos A - 0.0007 * E \quad \text{(Equation 4.2).}$$

This model had a R^2 of 0.64 and a Mallow's C(p) of -0.06, and it was significant at p = 0.004. Partial R^2 values show that MAP explained 45% of the variability in feature length, followed by 9% for hillslope gradient, 7% for cosine(aspect), and 4% for elevation. The multivariate model (Equation 4.2) tended to over-predict shorter features and under-predict longer features.

Rill gradients tended to decrease with distance from the top of the rills (r^2 = 54%; p = 0.03; Figure 4.5). Discharge also tended to decrease with increasing distance from the top of each rill, but rill width and rill depth did not show a strong, consistent relationship with the distance from the top of rill. In some rills rocks, roots, or trees affected the size and shape of the rill, and the resulting abrupt changes in gradient, channel dimensions, and calculated discharge helped explain the lack of a consistent relationship between these variables and either the relative or absolute distance from the top of each rill.

Six of the fifteen rills and none of the sediment plumes were directly connected to the stream. Five of the six connected rills originated from skid trails and the remaining rill originated from a clearcut. The connected rills ranged in length from 12 m to 220 m (Figure 4.2), and the shorter lengths indicating that skid trails sometimes were within the SMZ.

Connectivity was not related to rill slopes, as the connected rills occurred on slopes ranging from 11% to 32%. The average length of connected features was 60 m as compared to 26 m for the unconnected features, but the highly skewed distribution means that excluding the longest rill (220 m) causes the mean length of the connected rills to drop to 28 m, or nearly the same mean length as the unconnected features. Surprisingly, the connected features tended to occur in areas with lower MAP, as the MAP for the connected features was only 660 mm as compared to the MAP of 910 mm for the unconnected features.

Univariate analyses showed only weak relationships between connectivity and the individual predictor variables of MAP, feature length, feature gradient, time since disturbance, soil erodibility, soil depth, elevation, and cosine (aspect). An attempt to predict connectivity with feature length using Fisher's Exact test was unsuccessful ($p = 0.34$). Similarly a model developed to predict connectivity from feature slope showed only a weak relationship ($p = 0.99$).

4.6 Discussion

The source of each feature was either a water bar on a skid trail or a clearcut, and this provides insights into the causative processes and implications for managers. Like roads, skid trails are typically compacted, and the lower infiltration rate means that overland flow can be readily generated (Croke and Mockler, 1999a; Lacey, 2001; Ziegler *et al*. 2000). The overland flow generated by skid trails will increase erosion and sediment transport rates (Luce and Black, 1999; Coe, 2006). For these reasons water bars are required on steeper slopes to divert the overland flow from skid trails onto the more permeable hillslopes. If water bars were installed more frequently, drainage areas would be smaller and this would reduce overland flow, sediment production, and the likelihood of sediment delivery to streams (Croke and Mockler, 2001; Coe, 2006).

Both qualitative observations and the data indicate that the runoff from skid trails was more likely to form a rill or sediment plume if the area below the water bar had low surface roughness. In some cases, tractor tracks or logs provided enough surface roughness to stop a rill from further development. Sediment travel distance below water bars can be reduced by depositing litter or slash to increase surface roughness (Ketcheson and Megahan, 1996). Feature measurements indicated that some skid trails ran through SMZs as some features less than 45 m were connected to streams. The placement of skid trails should be considered carefully to avoid SMZs and the increased connectivity of features to streams.

Ripping of skid trails is sometimes used to restore infiltration rates. U.S. Forest Service personnel had suggested that erosion can sometimes occur along a ripped furrow when the skid trail is built across the contour of the hillslope. Since none of the features found in this study originated from ripped skid trails, this indicates that ripping skid trails is successful in reducing overland flow.

Areas that have been clearcut with ground-based logging equipment also can generate overland flow and surface erosion. In recent years, the amount of clearcut treatments on federal lands has been reduced due to the potential for adverse consequences on soils, water, plant and animal diversity, aesthetics, and recreation (Backiel and Gorte,1992). If the harvest is a selection cut or thinning, typically not all of the area is disturbed, and this will reduce the likelihood of overland flow and rill initiation. It is noteworthy that the three longest gullies all came from a clearcut with coarse-textured, granitic soil and rocky outcrops. The clearcut was covered sparsely with grasses, and another clearcut was upslope. The combination of a highly erodible soil, low surface roughness, and potential overland flow from upslope led to the development of the longest gullies found in this study. The Forest Service has since mitigated the erosion at this site. The implication is that older clearcuts should be monitored for legacy features that still generate and deliver sediment to streams, and such sites should be further treated to minimize surface runoff and erosion.

One of the more remarkable findings from this study is the small number of features identified through the field inspection of 200 harvest units. Since the 1990's the number and size of clearcuts have been greatly reduced on national forest lands, and much more of the timber is being harvested by thinning and group selection (Backiel and Gorte, 1992). Three of the four NFs in this study fall within area regulated by the Herger-Feinstein Quincy Library Group (HFQLG) Forest Recovery Act (1998) Pilot Project. Under this project from 13,000 to 29,000 ha, or 2-4% of the total Pilot Project area, are being harvested annually by group selection, individual tree selection, and thinning (HFQLG Pilot Project Implementation Team, 2007). Less than 50% of the canopy is being removed in the units being harvested under this project, and both hydrologic modeling and paired watershed studies indicate that this type and amount of timber harvest will have little or no effect on runoff at the watershed scale (Stednick, 1996; HFQLG Pilot Project Implementation Team, 2007). The remaining trees also provide canopy cover, ground cover, and surface roughness, so it should not be surprising that 16 of the rills or sediment plumes that were observed in these areas originated from skid trails while the remaining three came from clearcuts.

Most of the rills and sediment plumes also were found on harvest units on the east side of the four NFs examined in this study (Figure 4.4). These areas generally have lower MAP, but they are subject to higher-intensity, convective storms in the summer than the west side (USDA, 1983). Qualitative field observations indicated that there was much less litter and ground cover on the east side harvest units than on the wetter, west-side units. The results from the multivariate model for feature length further indicate the importance of surface cover, as the negative coefficient for cosine(aspect) indicates that the longer rills are associated with south-facing slopes. The south-facing slopes are hotter and drier during the summer, and typically have less vegetation and litter than the north, east, and west aspects (P. Stancheff, Plumas National Forest, pers. comm., 2005). The lower amount of cover means that south-facing slopes are more susceptible to rainsplash and surface sealing (McIntyre, 1958; Fox *et al*, 1998; Assouline, 2004) and hence are more likely to generate infiltration-excess overland flow. The lower amount of cover also means that they have less surface roughness, so runoff velocities will be higher and they will be more prone to surface erosion.

The weak relationships between feature length and the predictive variables may be due to the high spatial variability of the controlling variables. On the forest floor, tractor treads created a considerable amount of microtopogaphic variability, and the accumulations of litter, slash, and debris generated created a high local variability in surface roughness. These localized variations often occurred in combinations that effectively stopped overland flow and rill erosion. In addition, the soils data had a spatial resolution of 5 ha, and this means that the mapped soil depth and soil erodibility may not be accurate for a given location. Local variations in these variables are not represented in the data collected in this study, and this can help explain why these variables were not significant in the model to predict feature length.

The number of rills and sediment plumes originating from forest harvest units may be higher than the number reported here because these features may not persist over time. In the

Georgia Piedmont, USA, gullies associated with timber harvest filled in over one to two seasons (Rivenbark and Jackson, 2004). To more accurately characterize the connectivity of harvest units to streams, a study should begin immediately after harvest and continue for several years in order to account for the interannual variations in precipitation amounts and intensity. A study over multiple years also might allow the evaluation of dynamic factors, such as vegetation regrowth, on feature development, length, and connectivity (Dudziak, 1974). This type of long-term monitoring is necessary to accurately assess the number and importance of rills and sediment plumes for delivering runoff and sediment from harvested areas to streams.

4.7 Conclusions

This study investigated the frequency of rills and sediment plumes from timber harvest units and their connectivity to streams. The downslope edges of approximately two hundred harvest units on four National Forests were traversed in the Sierra Nevada mountains of California. A total of fifteen rills and four sediment plumes were found downslope of fourteen units. The mean length was 36 m, but the maximum length of 220 m occurred in an eighteen year old clearcut in an area of low surface roughness. Only six of the rills and none of the sediment plumes were connected to streams.

Sixteen of the 19 features originated from skid trails, and the other three features originated in older clearcuts with very coarse soils and sparse vegetative cover. More of these features were found in drier areas, and this suggests that the amount of surface cover and roughness may be an important control on the development of these features.

Multivariate analysis showed that feature length increases with mean annual precipitation, age of harvest units, cosine(aspect), and hillslope gradients ($R^2 = 0.64$). The downslope progression of features was often stopped by a reduction in slope and the presence of more organic matter and surface roughness such as litter, logging slash, and woody debris.

The results indicate that the construction and post-harvest treatment of skid trails is critical for reducing the delivery of concentrated flow and sediment from timber harvest units to streams. The likelihood of sediment delivery from harvested areas can be greatly reduced by constructing water bars more frequently along the surface to reduce the amount of concentrated flow at any one point; ripping the skid trail after harvesting to maximize infiltration; and ensuring that the hillslope below the water bar has as much surface roughness (e.g., litter and woody debris) as possible. The limited number of features found in this study suggests that current forest harvest activities and best management practices are largely effective in reducing rilling and sediment delivery on these four national forests in the central and north Sierra Nevada. Future research should continue to focus on the cumulative effects of unpaved roads and wildfires.

4.8 References

Assouline, S., 2004. Rainfall-induced soil surface sealing: a critical review of observations, conceptual models, and solutions. Vadose Zone Journal 3: 570–591.

Backiel, A., and R.W. Gorte, 1992. Clearcutting in the National Forests. Congressional Research Service (CRS) Report 92-607. www.ncseonline.org/NLECRSreports/Forests, accessed February, 2008.

Barrett, J.C. and W.J. Conroy, 2001. Evaluation of timber harvest impacts on water quality. In: J.J. Warwick (Editor), *American Water Resources Association Technical Publication Series* 1(1): 205-210.

Beschta, R.L., 1978. Long-term patterns of sediment production following road construction and logging in the Oregon Coastal Range. *Water Resources Research* 14(6): 1011-1016.

Bowles, J. E., 1986. *Engineering properties of soils and their measurement*. McGraw-Hill, New York, 218 pp.

Bracken, L., and J. Croke, 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrologic Processes* 21: 1749-1763.

Brown, T.C. and D. Binkley, 1994. Effect of management on water quality in North American forests. GTR-RM-248. USDA Forest Service, Fort Collins, CO 27 pp.

Brown, A.V., Y. Aguila, K.B. Brown, and W.P. Fowler, 1997. Responses of benthic macroinvertebrates in small intermittent streams to silvicultural practices. *Hydrobiologia* 347(1-3): 119-125.

Coe, D., 2006. Sediment production and delivery from forest roads in the Sierra Nevada, CA. M.S. thesis, Colorado State University, Fort Collins, CO, 117 pp.

Croke, J., P. Hairsine, and P. Fogarty, 1999a. Runoff generation and redistribution in logged eucalyptus forests, southeastern Australia. *Journal of Hydrology* 216: 55-77.

Croke, J., P. Hairsine, and P. Fogarty, 1999b. Sediment transport, redistribution and storage on logged forest hillslopes in south-eastern Australia. *Hydrological Processes* 13(17): 2705-2720.

Croke, J. and S. Mockler, 2001. Gully initiation and road-to-stream linkage in a forested catchment, southeastern Australia. *Earth Surface Processes and Landforms* 26: 205-217.

Croke, J., P. Hairsine, and P. Fogarty, 2001. Soil recovery from track construction and harvesting changes in surface infitration, erosion and delivery rates with time. *Forest Ecology and Management* 143: 3-12.

Croke, J., and P.B. Hairsine, 2006. Sediment delivery in managed forests: a review. *Environmental Reviews* 14: 59-87.

Croke, J., and M. Nethery, 2006. Modelling runoff and soil erosion in logged forests: scope and application of some existing models. *Catena* 67: 35-49.

Dudziak, J., 1974. Observations of development of slope rills in forest clearings of the Tatra Mountains. (In Polish with English summary). *Czasopismo geograficzne* 45(1): 31-45.

EPA, 2000. National Water Quality Inventory, 1998 report to Congress. http://www.epa.gov/305b/98report/. Accessed May 2006.

Fox, D.M., and Y. Le Bissonnais, 1998. A process-based analysis of the influence of aggregate stability on surface crusting, infiltration, and interrill erosion. Soil Science Society of America Journal 62: 717– 724.

Gee, G.W., and J.W. Bauder, 1986. Particle size analysis. In *Methods of soil analysis: Part 1.* Ed. A. Klute. Madison, WI, American Society of Agronomy: pp. 383-411.

Hairsine, P.B., J.C. Croke, H. Mathews, P. Fogarty, and S. P. Mockler, 2002. Modelling plumes of overland flow from logging tracks. *Hydrological Processes* 16(12): 2311-2327.

Herger-Feinstein Quincy Library Group Pilot Project Implementation Team, 2007. Status Report to Congress Fiscal Year 2006. USDA Forest Service, Pacific Southwest Region, Quincy, CA, 18 pp.

Higgins, J.J., 2004. *An introduction to modern nonparametric statistics*. Brooks/Cole, Pacific Grove, CA, 366 pp.

Jones, J.A., F.J. Swanson, B.C. Wemple, and K.U. Snyder, 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. *Conservation Biology* 14(1): 76-85.

Ketcheson, G.L., and W. F. Megahan, 1996. Sediment production and downslope sediment transport from forest roads in granitic watersheds. INT-RP-486, USDA Forest Service, Ogden, UT, 11 pp.

Kreutzweiser, D.P., and S. S. Capell, 2001. Fine sediment deposition in streams after selective forest harvesting without riparian buffers. *Canadian Journal of Forest Research* 31(12): 2134-2142.

Lacey, S.T., 2000. Runoff and sediment attenuation by undisturbed and lightly disturbed forest buffers. *Water, Air, and Soil Pollution* 122(1-2): 121-138.

Lane, P.N.J., and G.J. Sheridan, 2002. Impact of an unsealed forest road stream crossing: water quality and sediment sources. *Hydrological Processes* 16(13): 2599-2612.

Luce, C.H., and T.A.Black, 1999. Sediment production from forest roads in western Oregon. *Water Resources Research* 35(8): 2561-2570.

Madej, M.A. and V.Ozaki, 1998. Channel response to sediment wave propagation and movement, Redwood Creek, California. *Earth Surface Processes and Landforms* 21(10): 911-927.

McIntyre, D.S., 1958. Permeability measurements of soil crusts formed by raindrop impact. *Soil Science* 85: 185–189.

Megahan, W., 1972. An overview of erosion and sedimentation processes on granitic soils. *Proceedings of the Conference on Decomposed Granitic Soils: Problems and Solutions.* Redding, California. University of California, Davis.

Megahan, W. F. and. W.J. Kidd, 1972. Effects of logging and logging roads on erosion and sediment deposition from steep terrain. *Journal of Forestry* 70(3): 136-141.

Motha, J.A., P.J. Wallbrink, P.B. Hairsine, and R.B. Grayson, 2003. Determining the sources of suspended sediment in a forested catchment in southeastern Australia. *Water Resources Research* 39(3) 1056, doi:10.1029/2001WR000794.

Ott, R. L. and M. Longnecker, 2001. *An introduction to statistical methods and data analysis*. Pacific Grove, California, Duxbury.

Reid, L.M., 1993. Research and cumulative effects. PSW-GTR-141, USDA Forest Service. Albany, California, 118 pp.

Renard, K..G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder, coordinators. 1997. Predicting Soil Erosion by Water: *A guide to conservation planning with the Revised Universal Soil Loss Equation*. U.S. Department of Agriculture, Agriculture Handbook 703, 384 pp.

Rivenbark, B. and C. Jackson, 2004. Concentrated flow breakthroughs moving through silvicultural streamside management zones: Southeastern piedmont, USA. *Journal of the American Water Resources Association* 40(4): 1043-1052.

Shaw, E. A., and J.S. Richardson, 2001. Direct and indirect effects of sediment pulse duration on stream invertbrate assemblages and rainbow trout (Oncorhynchus mykiss) growth and survival. *Canadian Journal of Fisheries and Aquatic Sciences* 58: 2213-2221.

Troendle, C.A., and W.K. Olsen, 1994. Potential effects of timber harvest and water management on streamflow dynamics and sediment transport. GTR-RM-247, USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, 34-41.

Teale GIS Solutions Group, 1997. California Annual Precipitation. URL: http://gis.ca.gov/casil/gis.ca.gov/teale/precipa/

USDA, 2004. Best Management Practices Evaluation Program (BMPEP) 1992-2002 Monitoring Results. USDA Forest Service, Pacific Southwest Region, Vallejo, CA.

USDA Forest Service, 1986. Eldorado National Forest Soil Survey. Placerville, CA.

USDA Forest Service Tahoe National Forest Soil Survey, 2002. Adaptive Management Services Enterprise Team, Nevada City, California.

USDA Forest Service, 1983. Plumas National Forest Soil Survey. Beckwourth, CA

Walling, D.E., 1983. The sediment delivery problem. *Journal of Hydrology* 65(1983): 209-237.

Wheater, C. P. and P. A. Cook, 2000. *Using statistics to understand the environment*. New York, Routledge, 245 pp.

Ziegler, A.D., R. A. Sutherland, and T. W. Giambelluca, 2000. Runoff generation and sediment production on unpaved roads, footpaths and agricultural land surfaces in northern Thailand. *Earth Surface Processes and Landforms* 25(5): 519-534.

Table 4.1. Description of the five surface roughness classes.

Roughness class	Description
1	Bare mineral soil with little surface roughness.
2	Greater than 50% bare soil, 1-2 short sections with rocks or slash.
3	Greater than 50% bare soil and more than two short sections with rocks or slash.
4	Greater than 50% cover of vegetation and litter, and more than two sections with rocks or slash.
5	Dense cover of vegetation or litter with extensive slash, rocks, or woody debris.

Table 4.2. Feature and site characteristics in order of increasing feature length. MAP is mean annual precipitation.

RILL_ID	Rill (R) or plume (P)	Years since harvest	MAP (mm)	Total Length (m)	Connected (yes/no)	Feature gradient (%)	Roughness class	Aspect (°)	Soil erodibility (K)	Elevation (m)	Soil depth (m)	Sinuosity
Antelope4	P	2	635	10	n	20	1	45	0.23	1536	0.74	1.05
Ward_1	R	13	1016	10.8	n	36	2	0	0.27	1831	1.06	1.08
LowerC18_1	R	5	508	11	n	9	1	140	0.27	1763	1.46	1.05
Siegefried53_1	R	4	508	11.6	n	29	2	70	0.33	1787	0.47	1.05
Spike2_1	R	3	762	11.8	y	12	2	225	0.27	1844	1.08	1.16
BigC10_1	R	11	508	11.8	y	17	1	160	0.3	1747	0.87	1.11
BigC10_2	P	11	508	14.3	n	7	1	200	0.3	1749	0.87	1.16
Cate14_1	R	9	1016	16	n	18	1	0	0.18	1809	0.76	1.03
Verdi_1	R	10	762	18.3	n	14	3	220	0	1778	1.1	1.1
Antelope3	P	2	635	19.1	n	30	3	50	0.23	1543	0.74	1.14
Antelope2	P	2	635	21.7	n	26	2	50	0.23	1546	0.74	1.03
Antelope1	R	2	635	22	n	26	2	250	0.23	1543	0.74	1.07
Antelope5	R	2	635	25	y	28	2	170	0.27	1590	0.88	1.1
Spike9_1	R	11	762	29.6	n	14	3	300	0.27	1852	1.08	1.06
Blake7_1	R	8	889	33	y	17	2	180	0.19	1815	1.41	1.07
Poison21_1	R	5	635	58	y	32	2	240	0.3	1698	0.87	1.12
Alder_2	R	18	1270	68	n	13	1	270	0.24	1756	1.14	1.41
Alder_1	R	18	1524	80	n	22	1	270	0	1785	0.51	1.2
Alder_3	R	18	1270	220	y	11	1	180	0.24	1750	1.14	1.31

Table 4.3. Correlation matrix for the predictor variables with r values on top and p-values below. Significant relationships ($p < 0.05$) are in bold.

	Mean annual precipitation	Elevation	Slope	Soil depth	Soil erodibility	Cosine (aspect)	Rill Roughness class
Age	**0.54**	**0.51**	0.21	0.38	0.02	-0.11	-0.39
	0.02	**0.02**	0.40	0.11	0.95	0.65	0.10
Precipitation		0.44	0.15	0.26	**-0.58**	0.08	-0.05
		0.06	0.54	0.27	**0.01**	0.74	0.83
Elevation			-0.16	0.40	0.04	-0.04	0.13
			0.51	0.09	0.86	0.87	0.60
Slope				-0.28	0.18	0.13	0.09
				0.25	0.46	0.60	0.72
Soil depth					0.04	**-0.55**	-0.02
					0.86	**0.01**	0.93
Soil erodibility						-0.17	-0.05
						0.49	0.84
Cosine (aspect)							0.08
							0.75

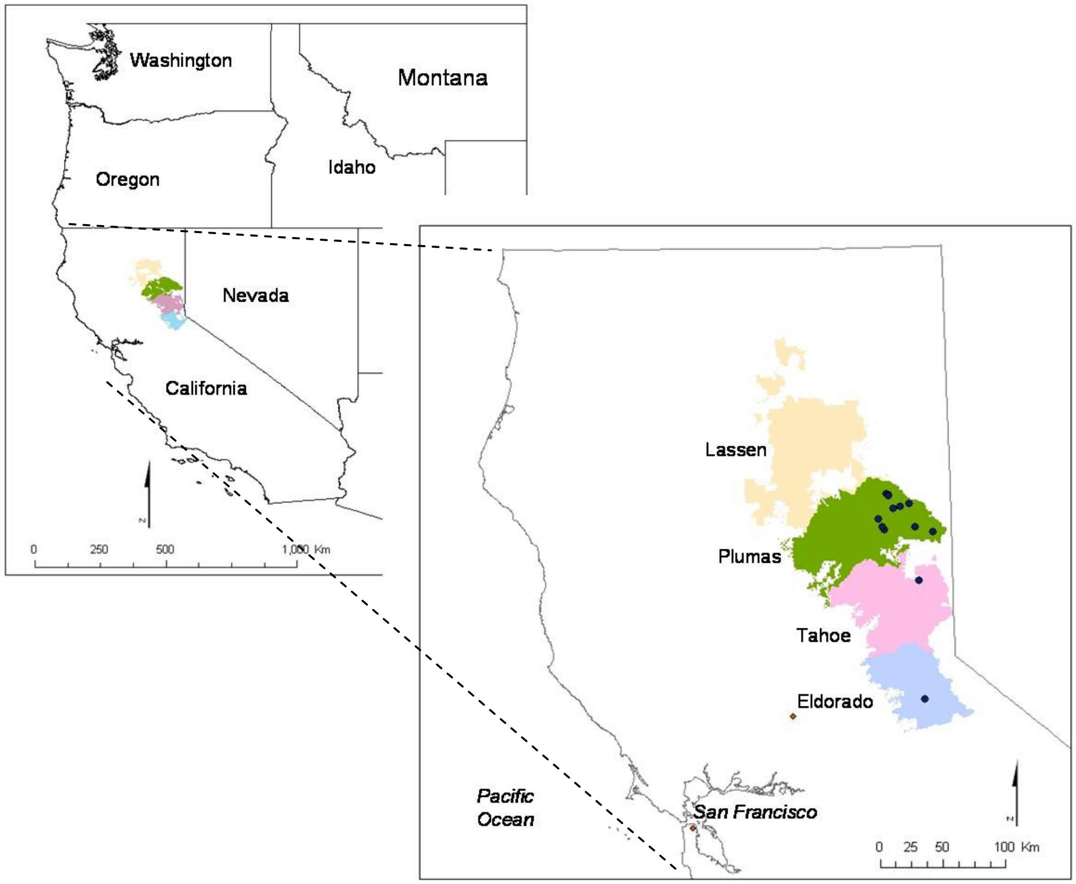


Figure 4.1. Location of the four National Forests used to assess harvest unit connectivity. The black dots indicate the location of one or more of the rills and sediment plumes identified in this study.

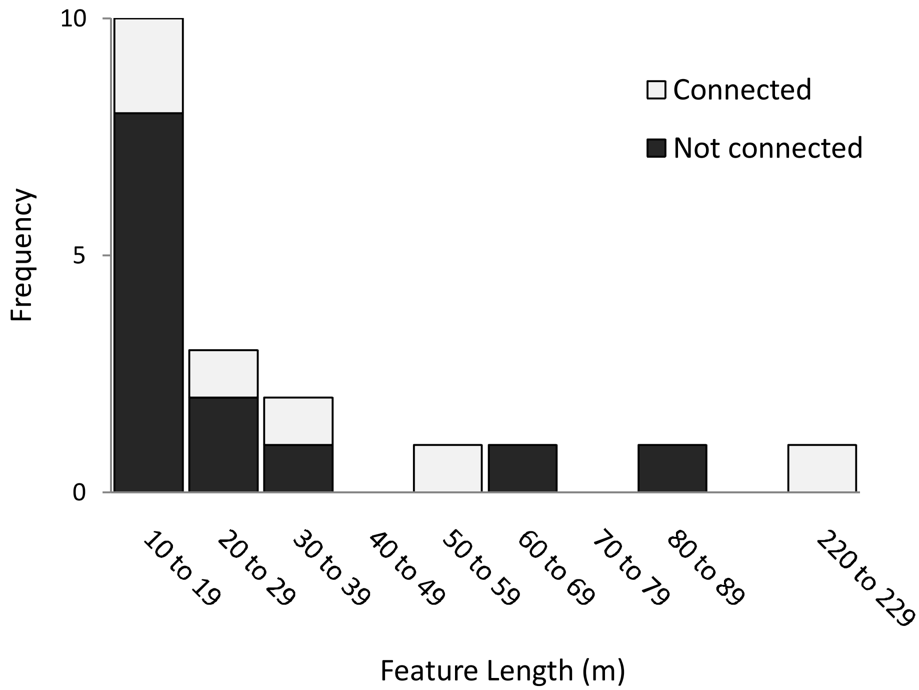


Figure 4.2. Frequency of features by length class and the number connected to a stream channel.

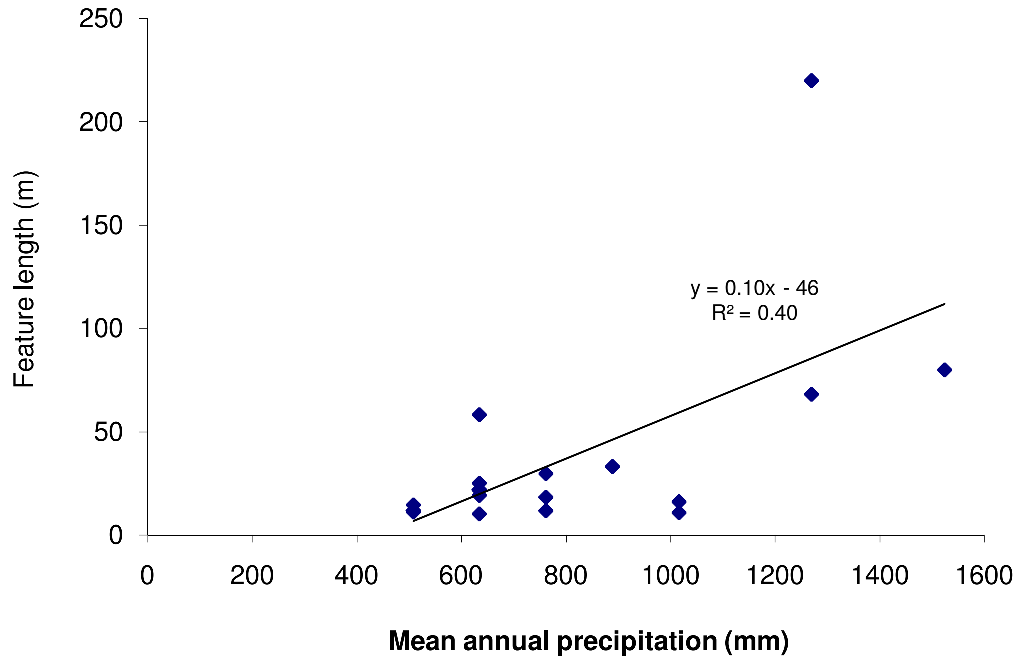


Figure 4.3. Feature length versus mean annual precipitation.

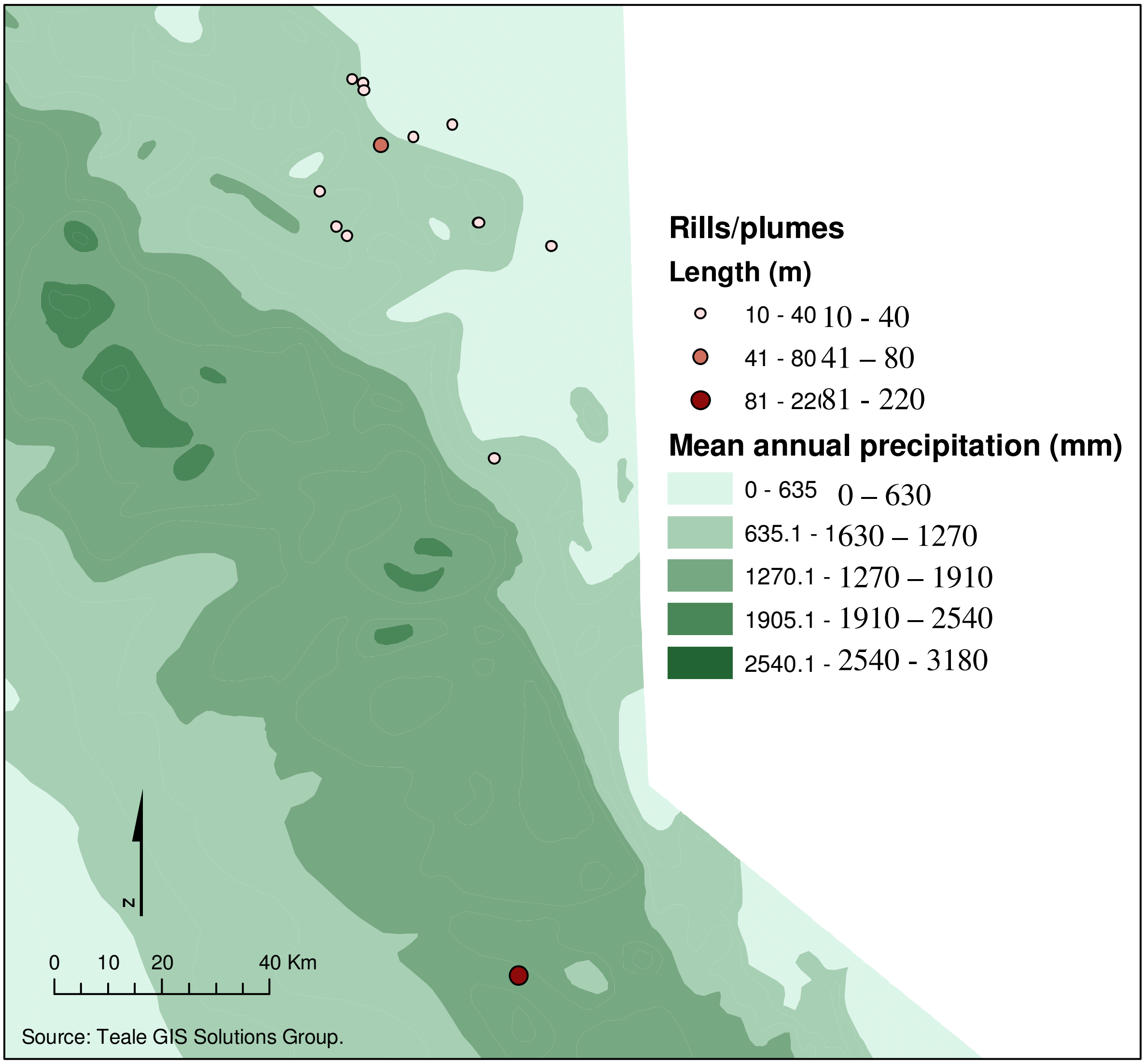


Figure 4.4. Feature locations and mean annual precipitation. Some symbols represent more than one feature.

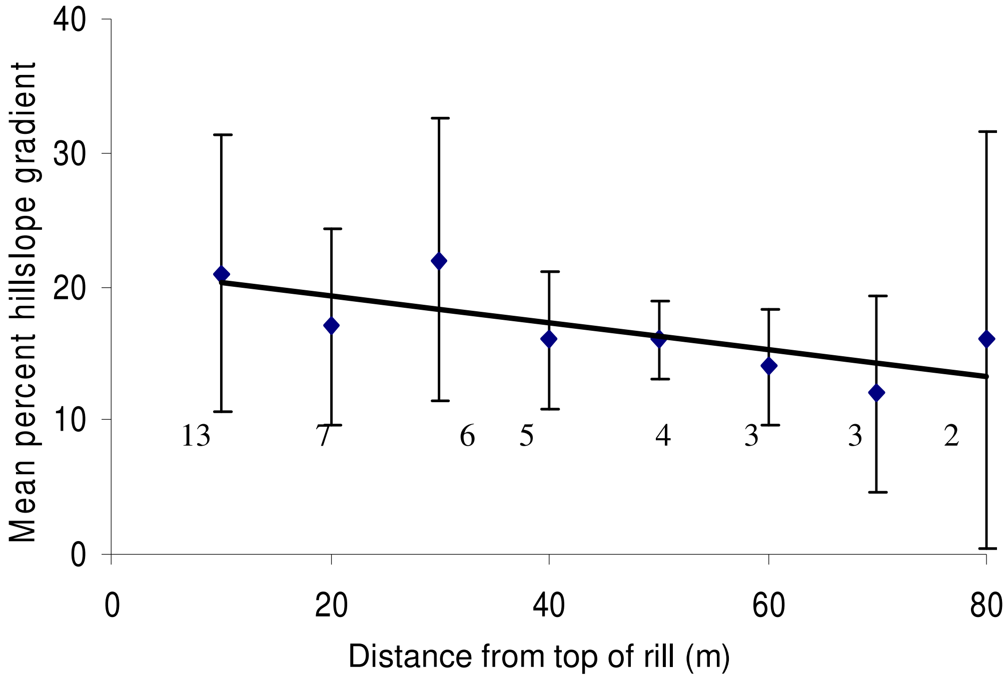


Figure 4.5. Average hillslope gradients decreased with increasing distance from the top of the rills (r^2=0.54; p=0.04). The bars show one standard deviation and the values below each bar represent the number of rills.

Chapter 5. Conclusions

The ability to assess and predict cumulative watershed effects (CWE) is critical for land managers proposing new projects. CWE assessments are also needed for maintaining and restoring aquatic and riparian health, and for managing water quantity and quality. This research has 1) developed two models, Delta-Q and FOREST, for predicting and assessing spatially explicit CWE; 2) verified the models using data from Eldorado National Forest; 3) validated the models with data from three experimental watersheds; 4) conducted sensitivity analyses of the models; and 5) investigated the presence and connectivity of rills and sediment plumes from forest harvest units to streams.

5.1 CWE models: Delta-Q and FOREST

The need was identified for a series of scientifically based, conceptual and empirical CWE models that use readily available data, are easy-to-use, and are temporally and spatially explicit. Delta-Q and FOREST were programmed using empirical and conceptual models from the peer-reviewed literature and from look-up tables created from WEPP. The models are spatially explicit as they interface seamlessly with underlying GIS. The user is able to simulate CWE over time by selecting the years to be simulated, inputting GIS layers with the years and types of disturbance, and selecting the number of years to full recovery after each type of disturbance.

Delta-Q calculates percent and absolute changes in runoff based on type of disturbance; a linear recovery is assumed over time. FOREST predicts sedimentary CWE by calculating sediment production and delivery from hillslopes and roads, and sediment routing through streams. Each model uses GIS data that are generally available; other data are provided in online help documents. The graphical user interface allows users to provide their own data if available. Outputs are in the form of tables for annual changes in water yield and sediment yield for each watershed. In addition GIS layers are generated for hillslope and road sediment production, and the stream layer contains sediment delivered from hillslopes and roads. Model verification confirmed that the models functioned as designed with respect to the internal logic, calculations, and GIS outputs.

The models were evaluated using data from Caspar Creek (CA), H.J. Andrews (OR), and Mica Creek (ID). Predicted changes in flow were more accurate for the 50th percentile flows than the more extreme 1st and 99th percentile flows. Predicted bedload sediment yields usually fell within the range of measured values, while the suspended sediment yields were sometimes overpredicted. Interannual climatic variability and the legacy effects of historic timber harvest practices sometimes precluded a good comparison between measured and predicted values.

Sensitivity analyses were conducted by varying DEM resolution and hillslope length, mean annual precipitation, and maximum arc lengths for streams and roads. Sediment delivery rates for the 30 m DEMs and 60 m look-up tables dropped by 90-98%

from the 10 m DEM and 20 m look-up tables (Figures 3.11 and 3.12). Increasing the mean annual precipitation by 25% increased hillslope sediment delivery by up to 20% and road sediment delivery by up to 35%. Decreasing the mean annual precipitation by 25% resulted in increases up to 12% in hillslope sediment delivery which were attributed to the sparser vegetation and reduced surface roughness of a drier climate (Table 3.12). Reducing the maximum length of stream arcs had relatively minor effects unless stream arcs did not follow the DEM. When streams veered away from the lowest flowpath through a DEM, FOREST either found an error in downstream connectivity or for smaller errors, bedload sediment yields were greatly reduced. Reductions in the maximum road arc length to 100 m increased the predicted sediment production by up to 137% above roads with unaltered arc lengths (Table 3.11). These increases are due to the increased steepness in road gradients as maximum road arc lengths decrease (Figure 3.16). Limiting the maximum road arc length to 100 m relative to the unaltered road arc lengths increased road sediment delivery by up to 211% (Table 3.11). The large increases in road sediment delivered are affected by the increased road sediment production and by the spatial distribution of roads as where roads are closer to streams, more sediment is delivered.

5.2 Sediment delivery pathways from harvest units to streams

Rills and sediment plumes that originated from timber harvest units were identified and measured in four National Forests in the central and northern Sierra Nevada mountains of California. A survey of the downslope edges of nearly 200 harvest units found only fifteen rills and four sediment plumes, plumes that originated in the harvest units and extended at least 10 m into a streamside management zone. Six of theses 19 features extended to the stream channel, five of these six connected features originated from skid trails. Features ranged from 11 to 220 m long. Longer features were associated with higher mean annual precipitation, older harvest units, and steeper hillslopes. Multivariate analysis showed that length was significantly related to mean annual precipitation, cosine(aspect), elevation, and hillslope gradient ($R^2 = 64\%$, $p = 0.004$).

The small number of features identified indicates that modern timber harvest practices are effective for minimizing runoff and erosion. Land managers should concentrate mitigation and restoration efforts on skid trails, roads, fire sites, and older harvest sites. Skid trails are a major concern as they affect forest hydrology similarly to roads. The results indicate that skid trails should be kept out of the streamside management zones and attempt to follow along the contour of disturbed hillslopes. Frequent installation of water bars are needed to drain the accumulated surface runoff downslope to the more permeable hillslope. Surface runoff on hillslopes also can be slowed and reduced using roughness elements such as microtopography, slash, or litter (Ketcheson and Megahan, 1996). Skid trails can be promptly decommissioned when no longer needed to minimize the accumulation of surface runoff. Finally, the monitoring of legacy sites is encouraged as continued restoration is occasionally needed.

5.3 Management recommendations for CWE modeling

Land managers will need to choose CWE tools according to their modeling objectives and expectations, location, organizational skills and limitations (Wilcock *et al.*, 2003; Caminiti, 2004; Elliot *et al.,* 2006). Delta-Q and FOREST are designed to be easy to use with minimal, readily available data inputs. They provide spatially and temporally explicit results in the form of GIS layers and tables. Delta-Q can be used to estimate changes in 1^{st}, 50^{th} and 99^{th} percentile flows. Percent changes in 99^{th} percentile changes in flow are an optional input into the sediment routing component in FOREST. FOREST generates hillslope and road sediment production layers that can be brought into ArcGIS to identify source areas for sediment. The source areas may then need ground-based investigation to determine specific needs for restoration or mitigation. FOREST also predicts sediment delivered from hillslopes and roads to each stream arc and these data indicate stream reaches at risk for sedimentation. Tabulated sediment yields show the predicted levels of sedimentation at watershed outlets.

Delta-Q and FOREST were designed to be used with multiple land use scenarios such that land mangers could easily compare the likely CWE for different proposed scenarios. Scenarios also can be compared spatially by mapping the GIS layers for hillslope sediment production, road sediment production, and sediment delivery streams. Annual and overall sediment yields can be compared for watersheds so that land managers can document and support scenarios that minimize CWE.

Land managers will need to be familiar with their data, sites, and the modeling process to optimize model use. Delta-Q and FOREST may not be able to detect data errors. The user must be aware of potential effects of any errors in their spatial data.

Ideally, land managers have sufficient knowledge of their sites and the modeling process such that they would recognize unlikely results due to data. Model diagnosis is facilitated by the many data layers generated by FOREST and these can be visualized in GIS software to detect potential problems and errors.

5.4 Future research

Recommendations for future research fall into the three broad categories of data, models, and CWE tools. Data from other long term studies and different locations would be beneficial to further evaluate Delta-Q and FOREST. More data also are needed to derive models for other locations and to provide alternative methods for calculations so that users can choose sub-models appropriate for their sites. Delta-Q and FOREST are designed to be modular such that other models can be easily added to increase capability and update modeling processes.

Delta-Q and FOREST provide a basic set of CWE tools that could be enhanced by future additions, such as modules that calculate mass movements or bed and bank erosion. In FOREST, the background rate for sediment production implicitly includes mass movements but increases in mass movements are often associated with forest disturbances (e.g. Grant and Wolff, 1991; Cafferata and Spittler, 1998; Jones, 2001; Dhakal and Sidle, 2003). A module that predicts mass movements would greatly expand the geographic applicability of FOREST.

An independent evaluation of Delta-Q and FOREST by individuals not familiar with the models would increase credibility of the models for the purposes of litigation. A model assessment could consist of a ranking procedure where Delta-Q, FOREST, and other models are ranked for ease of use, cost of use, GIS and field data availability, user and technical documentation, model and data handling, number of input parameters, and accuracy of predictions.

In summary, Delta-Q and FOREST are designed to provide a middle-ground to CWE modeling by being easy to use, using readily available data, requiring few parameters, and by being spatially and temporally explicit. It is hoped that the use of these models will help land managers to maintain and restore the condition of our forested watersheds as well as providing clean water supplies to downstream communities.

5.3 References

Cafferata, P. H., and T. E. Spittler, 1998. Logging impacts of the 1970's vs. the 1990's in the Caspar Creek watershed. USDA Forest Service Report PSW-GTR-168**,** p.103-115.

Caminiti, J.E., 2004. Catchment modelling - a resource manager's perspective. *Environmental Modelling & Software* 19(11): 991-6.

Dhakal, A. S., and R.C. Sidle, 2003. "Long-term modelling of landslides for different forest management practices." *Earth Surface Processes and Landforms* 28:853-868.

Elliot, W.J., K. Hyde, L.H. MacDonald and J. McKean, 2006, March 21(last update). Tools for analysis. In: W.J. Elliot, and Audin, L.J., (Eds.), DRAFT Cumulative Watershed Effects of Fuels Management in the Western United States. [Online]. Available: http://forest.moscowfsl.wsu.edu/engr/cwe/.

Grant, G.E., and A.L.Wolff, 1991. Long-term patterns of sediment transport after timber harvest, Western Cascade Mountains, Oregon, USA. In *Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation*. Proceedings of the Vienna Symposium. IAHS Publication No. 203, p. 31-40.

Jones, J. A., F.J. Swanson, B.C. Wemple, and K.U. Snyder, 2001. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. *Conservation Biology* 14(1):76-85.

Ketcheson, G.L., and W. F. Megahan, 1996. Sediment production and downslope sediment transport from forest roads in granitic watersheds. INT-RP-486, USDA Forest Service, Ogden, UT, 11 pp.

Wilcock, P.R., J.C. Schmidt, M.G. Wolman, W.E. Dietrich, D. Dominick, M.W. Doyle, G.E. Grant, R.M. Iverson, D.R. Montgomery, T.C. Pierson, S.P. Schilling, and R.C. Wilson, 2003. When models meet managers: examples from geomorphology. In Wilcock, P.R., and R.M. Iverson (Editors). *Prediction in Geomorphology*. AGU, Washington, D.C., 256 pp.